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Feel the Music

Alice Haynes (Engineering Mathematics)

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Supervisor: Dr J. Lawry, Engineering Mathematics

"Feel the Music"

Exploring tactile mappings of auditory stimuli as a step toward making music more accessible for those that are deaf or hearing impaired.

By

ALICE HAYNES

Supervised by: Dr. Jonathan Lawry
Dr. Jonathan Rossiter
Dr. Chris Kent

Department of Engineering Mathematics
UNIVERSITY OF BRISTOL

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Abstract

Music has been an integral aspect of societies and cultures across the globe for millenia. It is an engaging form of expression and communication that can convey powerful messages, evoke emotional responses and even affect our physiological rhythms. For those with hearing impairment or deafness it is difficult to experience music in the acoustic sense. This work looks to extend the current field of research into tactile sensations and the emotions they elicit with an aim to map music into the haptic domain. The motivation is to create a prototype wearable device that could aid those with hearing impairments to experience music via sensory substitution.

There is little current research into emotional responses engendered by tactile sensations or the viability of utilising a haptic interface to experience music. We address this through formal experimentation combined with the development of a novel wearable prototype. Firstly, an initial experiment was undertaken to build a fundamental understanding of how tactile sensations are perceived and which features of sensation affect emotional responses. A small electromagnetic solenoid device was used to create sensations on the index fingertip of 20 participants while they rated the stimuli in a 2D space of Arousal vs Valence, referred to as the Circumplex Model of Affect. Results found that certain features of the tactile stimuli presented such as frequency and waveform shape had significant correlations with the Arousal and Valence responses, while other features did not. Correlations with Arousal were generally found to be consistent across participants while Valence responses were much more subjective.

Exploiting knowledge gained from this experiment, a prototype wearable tactile stimulation device was designed, fabricated and tested that generated sensations through 8 vibrational motors on the forearm and a novel squeezing module on the upper arm. This prototype was tested on 20 different participants with good hearing. They were asked to rate their Valence response and select three adjectives taken from the Hevner adjective circle to describe the experience. Mappings were generated from 7 music samples onto the device and participants were presented with the music samples and these tactile mappings separately then combined for comparison. Further tactile stimuli were composed by hand for the device.

Responses varied greatly across participants and while there was evidence to suggest that the tactile mappings successfully represented the respective music samples, further experimentation would be necessary to verify this. The wearable tactile device successfully elicited a range of responses and demonstrated potential for a more sophisticated prototype to be capable of engendering emotions either as a new medium or as a substitution for acoustic music. This ambitious experiment has taken the first step to formally explore the perceptual space of tactile music and expand the boundaries of what we currently understand in sensory substitution using audio-tactile mappings. No previous projects utilising music based haptic interfaces have assessed their devices through such formal experimentation.

CONTENTS

1 INTRODUCTION

Though it is challenging for those with hearing impairments to experience music acoustically, for professional dancers and musicians that are deaf such as the National Deaf Dance Theatre troupe or well-respected percussionist Evelyn Glennie, music and rhythm are still accessible to them via visual and tactile cues. Research has found that the brain anatomy, in people with early deafness, is altered, causing greater sensitivity to vibration [1] [2] and other sensory modalities. This explains why many people with hearing impairment enjoy going to concerts and live performances to 'feel' the music, sometimes using accessories such as balloons to amplify the vibrations and enhance the experience. These ideas inspired the conception of this project, which looked to investigate the potential to replicate the affective qualities of music via the alternative medium of tactile sensations. This required a new understanding of how we respond to tactile stimuli and the intricacies of sensation combinations; an area in which there is currently very limited published research. Emotions evoked by music have been studied extensively throughout the past century and yet still remain a challenge to understand or generalise. It was expected that responses to tactile stimuli would be equally challenging to define; perhaps more so since music is a well-established medium of communication whereas tactile stimulation is not and is perceived differently from acoustic.

1.1 Intention and motivation

The intended outcome of this work was to extend the current research in the field of tactile interfaces and inter-domain mappings between sound and touch with the aim of understanding and stimulating emotional responses in the tactile domain. Specifically this project aimed to test how successful or even feasible a mapping between sound and touch could be as a basis for using tactile sensation as a musical interface. Whilst there are multiple uses of tactile interfaces currently employed in wide variety of fields, from gaming to notifications on your phone, this is an area of research that is lacking fundamental experimentation and subsequent analysis. A better understanding of human response to tactile sensations correlated with sound could open a multitude of possibilities, particularly for the deaf community.

1.2 Project structure

The project naturally falls into two complimentary parts. The first was to conduct an experiment investigating responses to parameterised artificial tactile stimulation in a small sample of participants with an aim to assess what features of haptic sensations affect user response. The second part of the project made use of these results to explore possible mappings between music and tactile sensations. In order to do this a prototype tactile interface was designed and created through which music could be channelled. A summary of objectives were as follows:

- Design and conduct a formal experiment to investigate the emotional responses elicited by tactile stimulation and identify what features of haptic sensations affect the user's response.
- Analyse the results of this experiment to inform our understanding of the haptic domain and it's affective qualities.
- Fabricate a prototype haptic interface capable of producing a range of sensations.
- Generate audio-tactile mappings from music samples into the tactile space defined by the prototype's interface and implement these onto the device.
- Conduct further experimentation to observe how the affective responses elicited by the mappings differ to responses engendered by the music samples.

2 BACKGROUND

Alternative sensory substitution has been implemented in a wide range of areas to aid those with varying forms of sensory impairment. It is now also being explored as an avenue of research in its own right to create new experiential modes of media and art. While most research to date employs mappings between visual-audio or visual-tactile domains, there are an increasing number of projects exploring the use of audio-tactile mappings. A few of these are specifically focused on creating musical experiences via tactile sensations.

This project overlaps with a number of existing research areas, sitting at the intersection between the psychological study of human response to sensory stimuli and the implementation of haptics in devices. Current projects / studies in both fields are outlined below in order to provide background to this project.

2.1 Existing haptic devices

Two wearable devices have been designed that reduce audio to its key features in the high, medium and low frequency ranges then output vibrations in three separate spatial areas across the skin. One is a collar designed by Frederik Podzuweit [3] to be worn around the neck that plays music from an ipod/phone for the hard of hearing. The other is a wrist worn device called Outer Ear [4], in which the sounds in the surrounding environment are fed to the device aiding the user in processing complex sounds through vibration. These devices are portable, stylish and have the potential to be affordable for individuals which is a fantastic prospect for people with hearing impairment. However, they are limited in their current capability for expression and adaptation since they only use one form of tactile stimulation in three localised points on the skin. Both projects are lacking sufficient research into the resulting quality of user interaction with the device, giving no evidence or experimentation to demonstrate that the tactile sensations created are effective in relation to their respective intentions.

A case study [5] has been carried out in London looking into designing tactile musical devices with and for deaf users. The outcome was a sofa/armchair set with voicecoil actuators embedded in the back and arms of the furniture creating an effectively full-body experience emulating that felt at a concert or live performance. Another project [6] focused on helping people with severe deafness by creating dance shoes with vibration nodes that communicate rhythms to the dancer so that they can keep in time with music without needing large sound systems or visual cues.

The MIT Media lab has adopted an approach which instead of applying some mapping between sound and touch, treats tactile stimulation as a new medium of its own [7]. Their device is a whole body suit using high frequency transducers spread evenly across the limbs and a large low frequency transducer on the back. Pieces were composed directly for the tactile experience, tested at the end of the project by conducting a 'tactile concert' in which audience members wore the device and experienced a series of pieces with different combinations of musical and tactile experience.

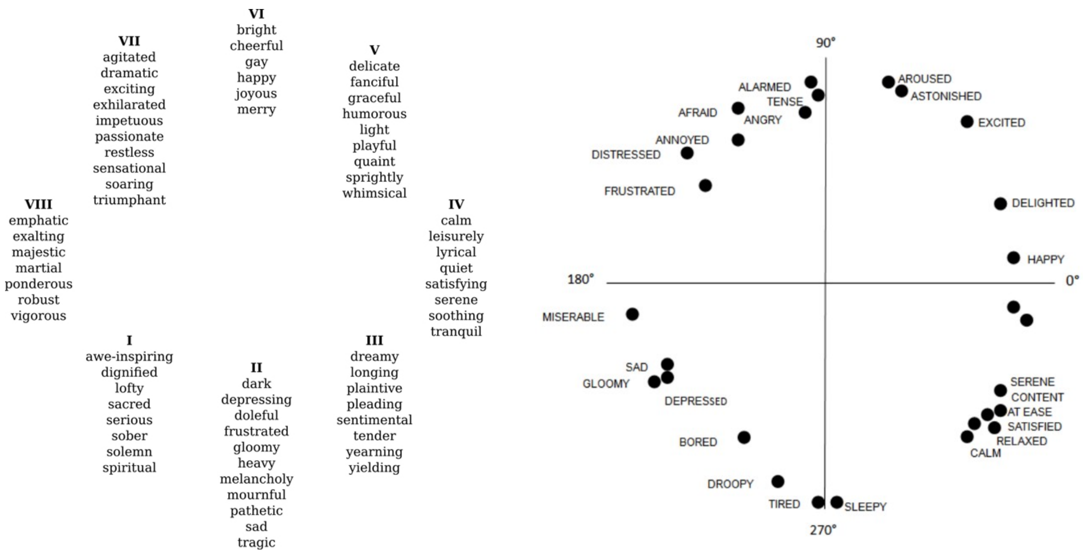
One of the most advanced projects currently working in the area of tactile communication and experience is 'VEST' [8] a project at Rice University run by David Eagleman [9]. They have created a wearable tactile vest that has been used and tested for multiple purposes. It works very effectively for deaf users to interpret speech, but also as a method of relaying real time data to the user subliminally. This was done by mapping information streams into vibration patterns that users began to interpret instinctively after a few weeks of training with the device.

2.2 Identification and classification of emotions

A successful mapping of music into a new sensory domain could be measured by the ability of the mapped sensations to elicit the same affective response as the original piece of music. Therefore, an understanding of affective response and how emotions are engendered by music is necessary to inform the experimentation carried out in this project. Classification of human emotions is a long standing area of research. One of the first clearly documented explorations of emotion was by Charles Darwin [10] in 1872. This and further key contributions throughout the 20th century from the likes of Tomkins, Gellhorn and Ekman, as discussed by C. E. Izard [11], are still very relevant in the field today. Modern research has the benefit of technology able to formally test further aspects such as physiological changes, some of which have been shown to relate to emotion [12], when participants are listening to music.

Various approaches to understanding and defining emotion were discussed by Paul Ekman and Klaus Scherer in 2014 [13]. Current models of emotion fall generally into one of two categories: the discrete model, defining 'basic' emotions as a set of characteristic describers such as anger, fear, enjoyment, disgust, surprise and sadness [14] [15]; and the dimensional model, sometimes referred to as the 'Circumplex Model of Affect' defining emotions as directions on a 2D space of Valence and Arousal [16].

There have been various approaches over the last century to create a discrete model of emotions. A key issue limiting the success of models relating specifically to music is that the emotional interpretation of a musical composition varies dramatically between listeners and relies on a multitude of factors such as harmony, timbre and lyrics [17]. Classification is also made difficult by the fact that the classes of emotions evoked by music are not mutually exclusive [18]. Hevner [19] carried out much celebrated work in this field, in particular finding that the differences between listeners' responses can be minimised by confining participants to choose from a list of adjectives and then clustering the adjectives into groups. This led in 1936 to the formation of a combined Adjective Circle [20] of descriptors which separates a list of 66 music adjectives into eight groups clustering adjectives together as shown in Figure 1a. This was expanded to ten groups by Farnsworth [21] in 1958. Numerous studies since have based their music mood classifiers on these adjective groupings. The GEMS scale [22] is one of the more sophisticated discrete models focused specifically on the emotions engendered by listening to music. The complete scale consists of 45 emotional state descriptors.



(a) Adjective Circle of descriptors according to Hevner [20].

(b) Circumplex Model of Affect according to Russell [16].

Figure 1

In recent years research into quantifying emotions has increased rapidly not only due to the internet providing easy access to digital music information, but also to the need for automatic classification and retrieval methods. The Music Information Research Evaluation eXchange (MIREX) [23] is a community of researchers and programmers that have been researching the broad area of music information retrieval since 2005. From 2007 onwards they have yearly submissions on Mood Classification in music. In this category the best results to date [Audio Classification Tasks: MIREX 2015 SUBMISSIONS] still fall below 70% successful classification and use complex methods with Support Vector Machines (SVM), exploiting multiple features such as Mel Frequency Cepstrum Coefficients (MFCCs), spectral features and chroma-based features. This demonstrates the difficulty of the task and complexities involved in music-based research.

There is some debate in the psychology literature as to whether the emotions evoked by listening to music are adequately described and classified by these 'basic emotion' models. The other key model introduced above is the Circumplex Model of Affect as shown in Figure 1b, which treats emotion as points or trajectories in a 2D space. The vertical dimension relates to Arousal (also referred to as intensity) and the horizontal dimension relates to Valence (also referred to as pleasantness). This is appropriate since it is widely accepted that individuals do not experience, or recognize, emotions as discrete, independent entities [24]. Dimensional models such as this treat emotions as continuous and avoid the discrepancies in the interpretations of adjective meanings. There have been alternative forms of this 2D model [25] [16] [26], but the model of Valence vs Arousal is the most frequently adopted and is generally described as being able to encompass all emotions. All of the emotions classified in the Adjective Circle model can also be plotted into the Circumplex Model so these methods are not completely independent.

Due to the widespread acceptance of the Circumplex Model for the classification of emotion and its applicability to multiple sensory modalities, it was logical to use this as a basis for classification of both sound and touch in the experimentation models for this project. Therefore it is important to look at the current research in the fields of music and tactile sensation that employ this model.

2.3 Music in the Circumplex Model

Jaimovich et al [27] undertook a public study of over 4000 participants was carried out in 2013, looking at their response to a variety of music samples via a self-report questionnaire and recordings of heart-rate and electrodermal activity during listening. The results of using a pictoral self assessment mannekin to measure pleasure and arousal when listening to samples of 16 different songs are shown in Figure 2. They discuss the difficulty in classifying emotions engendered by music that are perceived as more subtle and complex than the 'basic' emotions mentioned previously and used numerous measures of participant responses including the GEMS scale, the Likert scale, and variations on these called the Tension scale and the Chills scale. The Likert scale is a five point scale to measure attitudes, assuming that intensity of experience is linear for example 1 representing 'Very Unpleasant' to 5 representing 'Very Pleasant'.

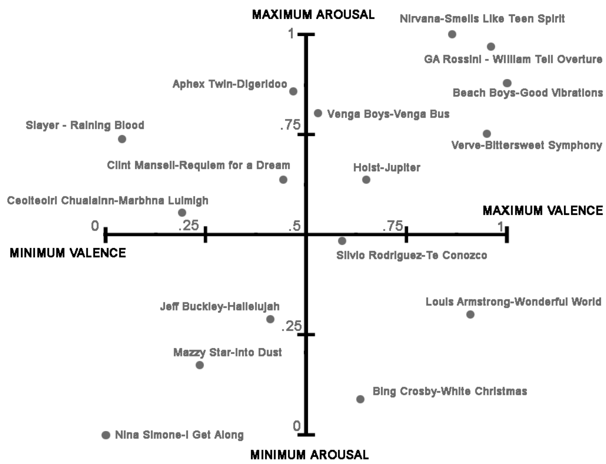


Figure 2: Results of 'Emotions in Motion: A study of music and affective response' [27] plotting song samples in the Circumplex plane according to listener responses.

The website project 'Musicovery' [28] used the Circumplex Model to create an interactive method of discovering new music. They engaged experts to classify songs according to 40 acoustic parameters which are employed by an algorithm (undisclosed) that plots each song onto the circumplex space. While the methodology is not available and may not be robust, it is interesting to note that each of the 16 genres included in the project evenly cover the entire circumplex space. This could be due to normalising each genre set across the space or it indicates that the genre of music does not limit the range of emotional response.

A further point of interest is that these two classifications of songs using the Circumplex Model - Jaimovich et al [27] and Musicovery [28] - do not agree; searching in the Musicovery space in Figure 3 for the songs used in the study as shown in Figure 2 finds over half located in a different quadrant of the space.

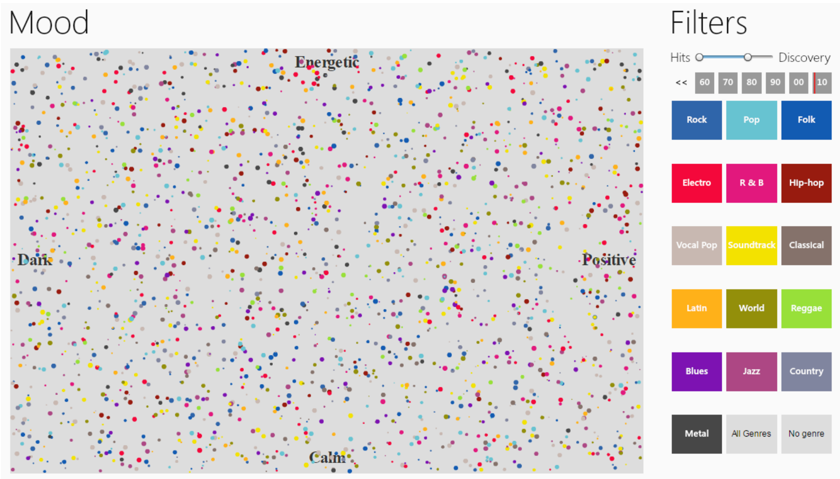


Figure 3: Musicovery [28] circumplex space containing thousands of songs colour categorised by genre. Arousal ('Calm' to 'Energetic') shown on the vertical axis, Valence ('Dark' to 'Positive') on the horizontal axis.

Kreutz et al[29] employed the use of the Circumplex Model to analyse emotional responses to music and found that classical/instrumental music is generally effective at inducing an intended emotion in listeners. However, the listener's preference for classical music had a strong influence on how effectively the piece induced the intended emotion. This could imply a general principle that inducing certain emotion through music is improved by listeners having an interest and understanding of the genre of music presented. Additionally, though five classifications 'happiness', 'sadness', 'fear', 'anger' and 'peace' were used, the results in the circumplex space clustered into three groups and suggest that listeners respond to 'anger' and 'fear' in a similar way and the same was found for 'sadness' and 'peace'. These emotions are considered very different in our general understanding of emotion, but in numerous studies it seems that our response to music has different distinctions in the emotion space. An example from this study is that increasing the 'sadness' of a piece appeared to increase the positivity of the listener response. This demonstrates the influence of aesthetics in music over and above the emotion being communicated; the 'sad' pieces were considered more aesthetically pleasing thereby inducing intensely positive emotions.

In a similar manner, the literature review and study by Panksepp et al [30] found that anxiety and anger were decreased by both 'happy' and 'sad' music, whereas sadness was increased by 'sad' music only and happiness was momentarily increased by 'happy' music only. It seems that despite these seemingly counter-intuitive relations, emotional responses to music given a participants background can be generalised such that responses of listeners can be predicted [31].

2.4 Tactile sensations in the Circumplex Model

Recently there has been a surge of interest in Sensory Modality; particularly research into the cognitive and emotional features of tactile information processing [32]. Tactile receptors in the skin vary across the body, but only recently has it been learned that certain neural fibres respond to specific tactile sensations. For example stroking sensations were found to be preferred to tapping and the two sensations induced different activity in the somatosensory system [33]. It was also found that participant responses were affected by whether the tactile stimulation was generated by an inanimate material or a human hand. Other studies using rats have suggested that both noxious (painful or negatively perceived) and non-noxious tactile stimulation could affect the levels of the hormone oxytocin which facilitates social behaviours [34] [35]. This small selection of studies demonstrates the complex nature of our relationship with tactile sensations and that there is a long way to go before we understand the subtleties of our neurological and physiological responses to touch.

In Suk et al [36] a tactile module consisting of 30 piezoelectric bimorphs was used to stimulate the fingertip of participants. They plotted the average response of nine participants in the circumplex space to 12 stimuli created by using three levels of amplitude (20μm, 50μm, 200μm) and four levels of frequency (2Hz, 5Hz, 25Hz, 100Hz). Their results are shown in Figure 4. Nine participants is a small sample size that may not be sufficient to generalise the results. However, it is interesting to see that even for this small group, there appears to be a relation between the frequency of the stimuli and the response of participants; as frequency increases, the stimuli are considered to be less pleasant and more intense. The relation between response and amplitude, however, is less clear.

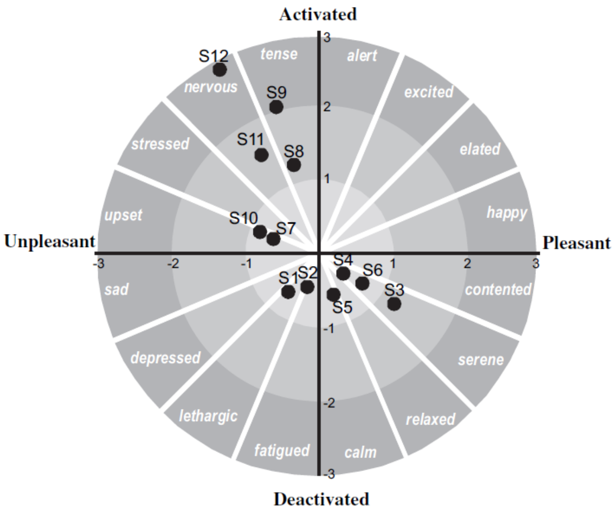


Figure 4: Results of the experiment by Suk et al [36] plotting responses to 12 tactile stimuli on the fingertip into the Circumplex Model according to Russell [16]

Another study employing the Circumplex Model for the classification of tactile sensations is Seifi et al [37], which attempted to categorise different tactile stimuli in the Circumplex Model as part of creating a tactile library. While the main focus of the study was looking to create an interface to aid tactile sensation choices for notifications, their methodology involved plotting a varied range of tactile stimuli in the Circumplex Model and hence is highly relevant to this project. The study uses 119 varied signals, some computer generated and some apparently recorded from life. However, there is unfortunately limited information on the experiment methodology and data sources. As part of the interface they have categorised the stimuli by plotting them in the circumplex space of Arousal and Valence. The signals and their rankings were available for use, giving us the opportunity to test the data for any relations between features of the signals and the response of the user in the circumplex space. These relations were used as a basis for the design of this project's experiment.

3 Initial Experimentation

The background work has shown that whilst interesting research has been undertaken into the way humans perceive tactile sensation, little has been carried out under rigorous experimental conditions. As a result it was necessary to test a number of the fundamental conceptions used in the project in more detail. Of foremost importance was to understand in more detail whether the haptic domain is one that can be utilised for communicating emotion. The first experiment aimed to discover what properties of tactile stimulation affect the emotional responses of participants and whether these are specific to the individual or can be generalised. If a generalisation could be found for both musical and tactile stimuli in the circumplex space then it would be possible to use this to create a mapping between the sound and touch domains.

3.1 Analysis of VibViz study data

Seifi et al [37], as discussed in Section 2.4, collected a set of data ranking 119 tactile stimuli in the interval between [-3,3] according to perceived Arousal, Valence, Energy, Tempo and Roughness. This data set was available for use, giving us the opportunity to gain insights into the design of the experiment for this project by first analysing this data for correlations between features and responses. Having a better understanding of stimuli features and their effect on user responses could inform the design of stimuli for our own experiment.

3.1.1 VibViz study set-up

The data used in the VibViz experiment was in the form of 119 wav files containing signals of varying shape, magnitude and length that were played via a tactor fixed on the wrist. A tactor is a small electromagnetic solenoid device with a central 2mm diameter 'contactor' that oscillates perpendicular to the skin according to an input electrical signal, as shown in Figure 5. The oscillation of the contactor is felt locally by the participant since the surrounding housing is fixed to the skin with adhesive tape. The frequency range is accurate within the interval [0,300] Hz which allows for the full range of frequencies that are distinguishable by the mechanoreceptors on a human fingertip. The study was not carried out or recorded rigorously and so much of the information on their experiment set-up and methodology is missing.

This lack of information caused two main difficulties when analysing their data. The first was that the data only contained the average results for each stimulus without indicating the variance of responses among participants. The second was that there was no indication of how the stimuli were chosen; some appear to be recorded sounds while others are computer generated and there is no relation between them. Four examples of the stimuli used are shown in Figure 6 to demonstrate this variation from which it can be seen how choosing features of the stimuli for analysis was a challenge. However, while this made it difficult to pick out features, the variation was useful to give an indication of how well the circumplex space could be covered. This was assuming that greater variation in the stimuli leads to greater variation in responses.

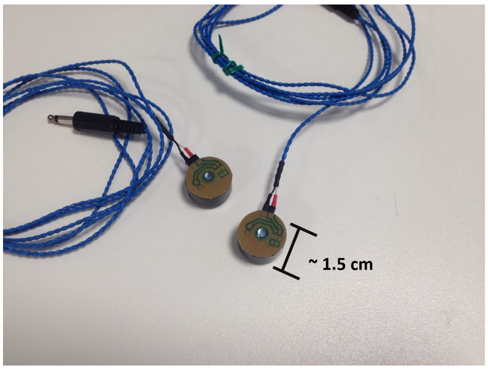


Figure 5: Two tactors identical to the one used in the VibViz study.

The result of plotting responses to the whole set of VibViz stimuli in the cirucumplex space is shown in Figure 7. The first noticeable quality of the data in the Circumplex Model is that it is not evenly spread across the space, but has an apparent negative correlation. In particular there is little data in the low valence, low arousal area of the space. This is demonstrated by the Principal Component of the data which is in the direction $y = -2.35x$ where y =Arousal and x =Valence as shown in Figure 7. This indicates some level of negative correlation between perceived Arousal and Valence as well as greater variance in the Arousal direction than the Valence direction.

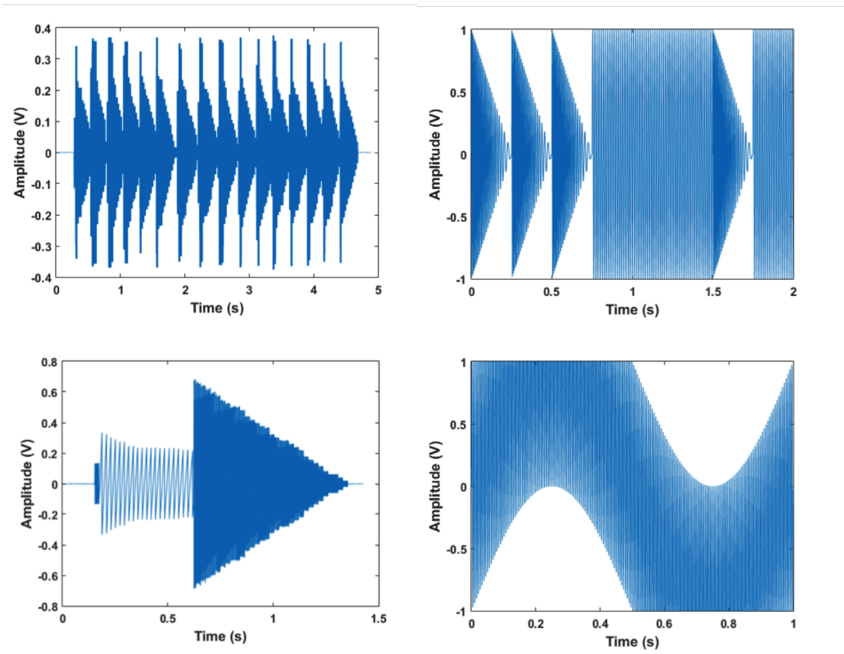


Figure 6: Four examples of stimuli used in Seifi et al [37] experiment demonstrating the variation in length, amplitude and form.

On first glance, the spread of the data appears to imply that the user typically found that the greater the perceived intensity of a tactile sensation, the less pleasant it seemed, whereas lower intensity tactile sensations were generally perceived as pleasant. However, these relations cannot be considered true in general due to our lack of knowledge of the true spread of the data and also there is a significant portion of the data in the pleasant/high intensity quadrant. The lack of extreme results for Valence in either the positive or negative direction is interesting to note since the stimuli are qualitatively varied so it was expected that they would create responses across the whole space. This suggests that either the stimuli chosen happen to not inspire strongly pleasant or unpleasant sensations (but others might), or it indicates that generally localised tactile stimuli do not elicit strong valence responses.

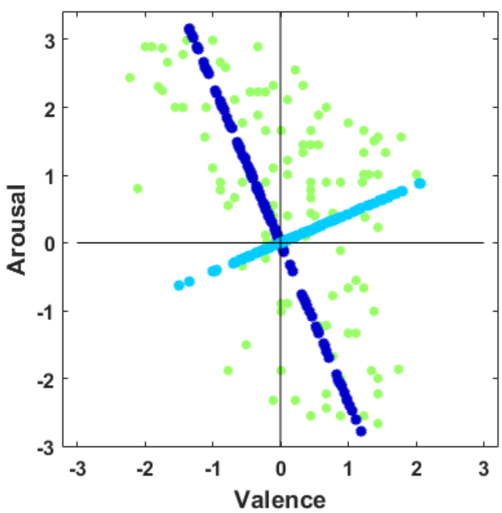


Figure 7: VibViz data plotted in the circumplex space (light green) with data projected onto the first (dark blue) and second (light blue) Principal Component Vectors. The gradient of the first component vector is -2.35.

3.1.2 Feature extraction

To investigate what aspects of tactile stimuli influence perceived Arousal and Valence, correlations between the responses and features of stimuli were calculated. This involved deciding upon and evaluating different features of the stimuli from the raw audio files supplied. Firstly, simple features such as the total energy in the signal, average amplitude and maximum amplitude were considered. The correlation coefficients $r(A,B)$ between these features and the five perceived attributes of Arousal, Valence, Tempo, Energy and Roughness were calculated using the covariance matrix according to the formula;

$$r(A,B) = \frac{cov(A,B)}{\sigma_A \sigma_B}$$

where A and B are two vectors that span the whole stimuli set and contain features to be compared, and σ_A, σ_B are respectively the variance of data in A and B. For example A could be a vector containing the values of total energy for every stimulus and B could contain the perceived Arousal value for each stimulus respectively and $r(A,B)$ would indicate the correlation between. A correlation coefficient r lies in the interval [-1,1] where 1 indicates a positive linear correlation and -1 indicates a negative linear correlation. Values close to zero indicate no correlation between the two sets of values. The first set of correlation results using the simple features described above are shown in Table 1 where it can be seen that all are close to zero and inconsistently positive and negative.

Before conclusions could be drawn from these correlation values it is necessary to define the scope of significance for the sample size. The value $r(A,B)$ is an estimate of the unknown true correlation $\rho(A,B)$ between A and B which can be used along with the sample size to assess whether or not ρ is significantly different from zero. To do this, a p-value table for 5% significance (ie that the true relation is equal to or more extreme than that measured with 0.95 probability) was referred to to find the minimum value of r needed to indicate a significant correlation in the data [38]. Since correlations of any kind, positive or negative, were being sought the p-value table for non-directional hypotheses were used. The result for a sample size of 119 at 95% significance was $r = \pm 0.181$. The highlighted results in Table 1 are those that exceed this threshold suggesting a correlation between these features and the perceived features. The energy per second in the signal was found to have significant correlation coefficients with Arousal, Valence and the principal component of these suggesting that the energy of a signal has an impact on the users response.

Stimuli Features	Correlation between stimuli features and perceived features:					Correlation with 1st component of
	Arousal	Valence	Energy	Tempo	Roughness	Arousal/Valence
Total Energy in Signal	0.0893	-0.1112	0.1212	**-0.2733**	0.0578	0.1028
Total Energy per Second in Signal	**0.2061**	**-0.1864**	**0.2580**	0.0646	**0.2145**	**0.2211**
Average Amplitude of Signal	**-0.1832**	0.0565	**-0.2069**	-0.0748	-0.0077	-0.1713
Maximum Amplitude of Signal	-0.0116	**0.2794**	0.0246	0.0157	-0.0474	-0.0746

Table 1: Coefficients of correlation between features perceived by participants and calculated features such as energy and amplitude of the stimuli signals. Total energy was calculated as the sum of squared signal amplitudes.

Frequency of vibration is another key attribute of sensation that humans can detect. Most of the VibViz stimuli signals varied in frequency over time making it difficult to find relations between frequency and Arousal/Valence directly. Therefore, new features were generated by examining the frequency spectrum of each stimulus signal by taking the fourier transform of the raw signal. In this way new features were calculated including the total energy and total absolute magnitude in the frequency spectrum for different frequency ranges.

The results of these correlations for 50 Hz intervals in the frequency space are shown in Table 2. Correlations were calculated with the total frequency range and 10 Hz intervals as well giving similar results. The largest correlations found were between the sum of magnitude in the frequency ranges 150-200Hz and the perceived Arousal and Valence with correlation coefficients of 0.4152 and -0.2310 respectively. These indicate that the

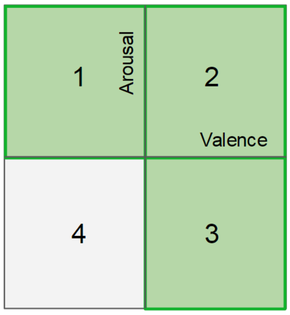
Features of frequency spectrum F	Frequency Intervals (Hz)	Correlation with Arousal	Correlation with Valence	Correlation with 1st PCA component of Arousal vs Valence
Total Energy	0 - 50	-0.0970	-0.0756	-0.0664
	50 - 100	-0.1521	0.0902	-0.1522
	100 - 150	0.0941	-0.0048	0.0824
	150 - 200	0.1762	-0.1535	**0.1877**
Total Energy in $log_{10}(F)$	0 - 50	-0.0575	-0.0633	-0.0350
	50 - 100	-0.0351	-0.0750	-0.0130
	100 - 150	-0.0449	-0.0699	-0.0226
	150 - 200	-0.0788	-0.0566	-0.0550
Sum of magnitudes	0 - 50	-0.1436	-0.1000	-0.1009
	50 - 100	-0.0254	0.0781	-0.0400
	100 - 150	0.1069	0.1695	0.0532
	150 - 200	**0.4152**	**-0.2310**	**0.4121**
Mean magnitude	0 - 50	**-0.2061**	0.0353	**-0.1863**
	50 - 100	**-0.2011**	0.1287	**-0.2035**
	100 - 150	0.0071	0.0471	-0.0048
	150 - 200	**0.2791**	-0.1432	**0.2742**

Table 2: Correlation coefficients between features derived from stimuli frequency spectrums and perceived features of Arousal, Valence and the principle component of these two. Frequency spectrums were calculated by performing a fast fourier transform on stimuli signals.

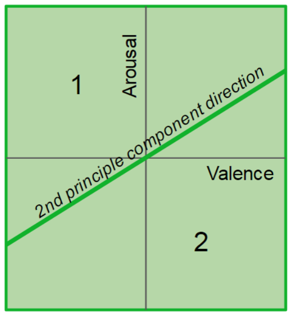
high frequency elements of a tactile stimulus have an impact on the users response. Additionally, three of the four coefficients of correlation between Arousal and mean magnitude in the frequency space are significant. The values in the 0-100Hz range for both mean and sum of magnitudes are negative whereas values in the 100-200Hz range are positive, indicating that increased magnitudes of high frequency components elicit greater Arousal responses and increased magnitudes of low frequency components elicit reduced Arousal responses. From this, inclusion of investigations into the effect of vibration frequency on emotional response in the experiment was noted and subsequently incorporated into the experiment for this project.

All correlations investigated so far assumed a linear correlation between features in the data and perceived features. Given the variety of the signals this was unlikely to be the case. Therefore a further method was used to investigate non-linear relations in the data using a multi-class Support Vector Machine (SVM) classifier. If a combination of features used to train the SVM resulted in a strong classification success rate when tested on a sample of the data, then it could be assumed that those features were related to the classes chosen. Classes needed to be identified for the training data. They were chosen to relate to the Arousal and Valence responses, while the SVM would be trained on features of the stimuli signals. Therefore, if successful, the SVM could take a new stimulus and predict the Arousal and Valence response based on the signal features.

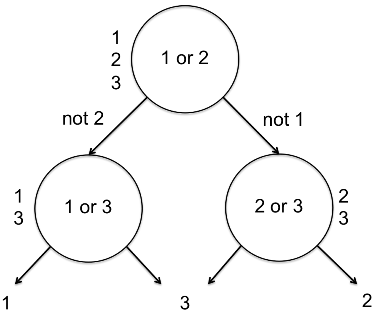
Two different class separations were tested for the data as shown graphically in Figure 8. The first method was to split the data by quadrant in the Arousal / Valence space giving the data in each quadrant a class value 1,2,3 or 4 according to the diagram in Figure 8a. Due to the lack of data in the low Arousal- low Valence quadrant, the data in quadrant 4 was ignored and the rest split into three classes. The data was split into 80% training data, 20% test data and a Decision Directed Acyclic Graph SVM (DDAGSVM) method used was to categorise the test data. The DDAGSVM can classify more than two classes by first of all classifying data into a pair of classes thereby ruling out one possibility, then classifying them again according to the remaining pair of possible classes as shown in Figure 8c. The method was tested for all three permutations of class order, the results for which are shown in Table 3. The average percentage of correct classifications by randomly assigning classes would be 33.3% for these classes. The results of the DDAGSVM are all higher than this so the classifier is able to do better than random selection. However, there is no verifiable method of determining what value is sig-



(a) 3 class division of data by quadrant in circumplex space. Data in shaded regions used for DDAGSVM.



(b) 2 class division of data by 2nd direction of PCA in circumplex plane. Data is shaded regions used for SVM.



(c) DDAGSVM method of 3 class classification by iteratively using a 2 class SVM to rule out classes in turn. Each circle represents testing data with an SVM trained on the classes labelled in the circle.

Figure 8: Methods of class separation used for SVM

nificant for a three class SVM and the values are not dramatically higher than random selection so no definite conclusion can be drawn from this.

The second method split data into two classes according to the PCA 2nd component vector as shown in green in Figure 8b. The motivation here was as follows. The 1st principal component is the direction of greatest variance in the data. If the greater variance in this direction is due to some feature or features of the signals, then splitting the data into two classes along this direction using the 2nd component should result in a high correct classification rate via the SVM. Unfortunately, as can be seen in Table 3, this method resulted in 54.2% correct classification of the test data which is close to 50%, in other words a similar result to randomly guessing the class.

	% correct classification DDAGSVM, 3 classes			% correct classification SVM, 2 classes
Stimuli feature space used for SVM	1 vs 2 first	1 vs 3 first	2 vs 3 first	1 vs 2 2nd component PCA
[Total energy , total energy/second, mean amplitude, maximum amplitude, total energy in the frequency spectrum]	36.4	40.9	40.9	54.2
Energy in signal frequency spectrum for (0 - 50, 50 - 100, 100 - 150, 150 - 200, 0 - max) Hz intervals	40.9	40.9	40.9	54.2

Table 3: Percentage of correct classifications using SVM on two different class separations. The first by separating the data into 3 classes (1,2 and 3 according to the circumplex space as shown in Fig 8) and using a DDAGSVM method to classify 22 test stimuli. All iteration combinations of the three classes were run; for example 1 vs 2 represents classifying data between classes 1 and 2 first, then class 3. The second by separating the data into 2 classes according to which side of the 2nd principal component vector the data lies in the circumplex space and using a standard SVM to classify 24 test stimuli. A Gaussian kernel was used in both methods.

The analysis of the VibViz data demonstrated that for an individual, correlations existed between some features of a tactile stimulus and the emotional response evoked, particularly features of the energy per second in the signal and magnitude of frequencies in the fourier space. This was a positive result indicating the potential of finding correlations between features of tactile sensations and the responses they elicit. However, the data was limited by the lack of participants and the non-parametrisable variation of the stimuli. The subsequent experiment for this project therefore required careful planning and formal procedure first to obtain clear evidence of whether or not these correlations can be generalised.

4 EXPERIMENT 1

Analysis of the VibViz data indicated that there may be general relations between response to a tactile sensation and features of the underlying signal. However, the high variation between stimuli and the lack of information about within-stimuli averaging limited our understanding of these relations. Therefore, the experiment undertaken for this project needed to obtain good coverage of the circumplex space using parametrised stimuli and focus on the within-stimuli variation of responses as well as across-stimuli responses in order to verify or counter the VibViz analysis findings. That the stimuli were parametrised was particularly important for the purpose of analysing relations between features of stimuli and participant responses.

First and foremost the experiment was designed to find out if emotional responses to tactile stimuli correlate to any key features of the stimuli signals, and secondly to observe if there is any consistency between participants responses as to the pleasantness/unpleasantness of vibration. If significant correlations could be found that were consistent across participants then this would provide clear evidence that tactile stimuli can be used to evoke emotions and that the engendered response relates to specific features of the sensations.

4.1 Experiment setup

The hardware chosen was an individual tactor made by 'Dancer Design' - mechanically the same as that used in the VibViz study as described in Section 3.1.1 - fixed to the index finger of the participant's non-dominant hand. The tactor was connected to the experiment laptop via a National Instruments Data Acquisition box that was wired up to output an accurate signal to the tactor, verified by returning the output signal to the laptop for comparison with the desired stimulus. All stimuli were validated through this setup to ensure no clipping or errors occurred when outputting signals. For example, the amplitude of stimuli was kept above $1V$ since some signals with lower amplitude were not produced accurately. Additionally, all stimuli were kept within the range permitted by the freedom of movement of the central contactor and at the end of each signal it was ensured that the contactor returned to resting position.

To avoid distraction, participants were given sound-cancelling headphones and sat in an individual booth with a laptop and mouse set up. For each stimulus presented in turn a window containing the circumplex space with horizontal axis labels [unpleasant, pleasant] and vertical axis labels [calm, intense] appeared on the laptop screen and participants were asked to click on the relevant position according to their reaction to the stimulus. Their mouse position was recorded when they clicked and the x and y values saved. The window is valued 700 by 700, so the coordinate (350,350) represented a completely neutral response. Stimuli were presented in two sections allowing for a break in between if desired by the participant and also separating two different classes of stimuli.

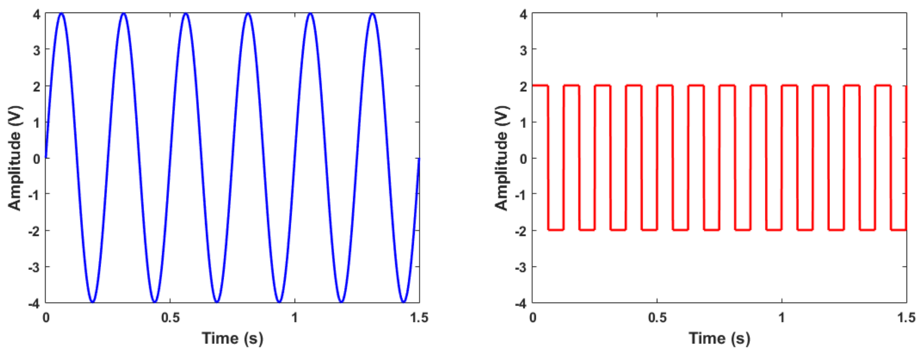
4.2 Participants

The participants were 20 undergraduate students at Bristol University from varying degree backgrounds. They all had dominant right hands (when using a computer mouse). The approximate age range was 19 - 23 years and of the 20 participants 12 were male and 8 were female.

4.3 Experiment stimuli

The stimuli for the experiment needed to take a broad variety of forms that could be generated by well defined parametrised waveforms. The first stimuli created were a set of sine waves with frequencies [2,4,8,16,32,64,128] Hz and amplitudes [2,3,4] V. The values were decided through experimentation with the tactors to determine a range that gave a variety of sensations. The frequency values increase logarithmically since it was found that lower frequencies are easier to differentiate between than high frequencies. For example, the difference in sensation between 2 and 4 Hz is much greater than between say 64 and 66 Hz. The parameters in this case are the frequency and amplitude of the signals which were easy to use as features of the stimuli when analysing relations between stimuli and participant responses.

These stimuli were repeated using a different waveform to verify whether correlations found between frequency or amplitude and participant responses were specific to the waveform type. A number of waveforms were tested including square waves, triangle waves, sawtooth waves and customised combinations of these. They were informally tested on numerous volunteers. The square waveform was reportedly the most qualitatively different in sensation to the sine waves, so this was used. In total this formed a set of 42 stimuli; 21 sine waves and 21 square waves, each including seven different frequencies and three different amplitudes for each. Two examples of these simple stimuli are shown in Figure 9.

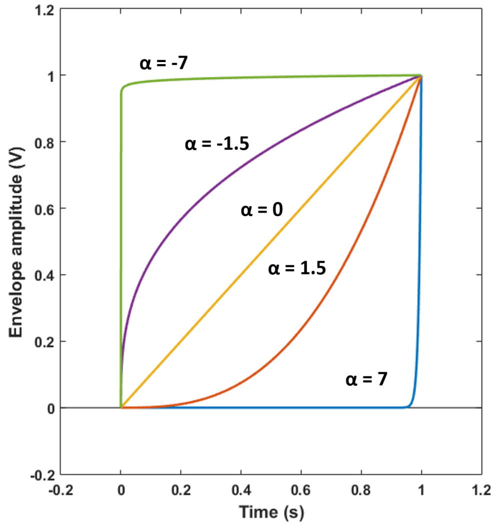


(a) Sine wave stimuli with amplitude 4V and frequency 4Hz. **(b)** Square wave stimuli with amplitude 2V and frequency 8Hz.

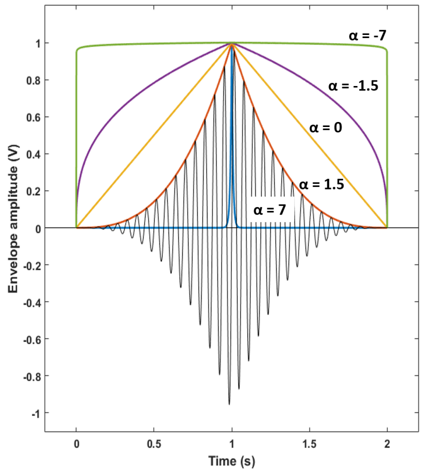
Figure 9: Example stimuli from the first set of generated signals.

With these stimuli as a basis, additional signals were then designed using more complex waveforms with the aim of covering all areas of the circumplex space. The challenge was in ensuring that the waveforms could be parametrised so that there was a known signal quality being varied that could be compared with the participant responses. A rich set of stimuli were created by multiplying a high frequency sine wave with an envelope waveform. Adapting this envelope to be a parametric function gave a set of signals that were qualitatively varied. The envelope types were simplified so as to have an increasing first half and a decreasing second half that respectively ended and started at equal amplitudes so they could be concatenated to create one waveform. Then the parameter value was chosen to vary the shape of the increasing part (decreasing part being a mirror reflection). Therefore, changing the parameter varied the onset and offset shape of the pulse, affecting the qualitative 'sharpness' of the sensation.

Creating the equation for these half envelopes required investigation of different functions and parameter values. The desired output of the equation was a set of smooth curves within a given interval that were qualitatively different and formed by varying a single parameter. Initially variations of the 'step function' form such as $y = \tanh(\alpha t)$, $y = 1/(t^{\alpha}+1)$ and $y = 1/(1+e^{-t/\alpha})$ were considered. However, it was difficult to get a good range of convex through to concave curves with these functions. After further experimentation the final family of envelopes was defined by adapting the function $y = t^{const^{\alpha}}$ to become $y = (t-c)^{2^{\alpha}}$ where c is a constant defining the start time and α takes the values [-7,-1.5,0,1.5,7]. The graphs for each of these alpha values are



(a) Demonstrating the increasing half of envelope function for all values of parameter α using the function $y = (t-c)^{2^{\alpha}}$, where t = time and c is the starting time, in this case $c = 0$. Decreasing envelope halves are created using $y = (1+c-t)^{2^{\alpha}}$.



(b) Concatenating increasing with decreasing parts of the envelope function to create a range of entire envelopes for each parameter value. Result of multiplying a signal by an envelope demonstrated on a 12Hz sine wave for $\alpha = 1.5$.

Figure 10: Generation of envelope waveform stimuli.

shown in Figure 10a for the increasing half of the envelope. As can be seen this equation gives five distinct shapes for which the parameter value influences the 'urgency' or 'sharpness' of the ascending curve.

To create the whole envelope an alpha value was chosen for both the increasing (α_1) and decreasing (α_2) halves which were concatenated together. Then the entire envelope was multiplied by the underlying wave which was chosen to be a sine wave of 64Hz. This frequency was chosen from the set of frequencies in the sine wave stimuli, 64 was high enough to smoothly define the waveform shape. The result was a single pulse of vibration that could be adapted to have any peak amplitude or time period and whose qualitative feel depended upon the combination of α values.

Both single and double pulse versions of these stimuli were made for all 25 combinations of α_1 and α_2 values resulting in 50 stimuli in total for this second set. Examples of the final stimuli created with this method are shown in Figures 11 and 12.

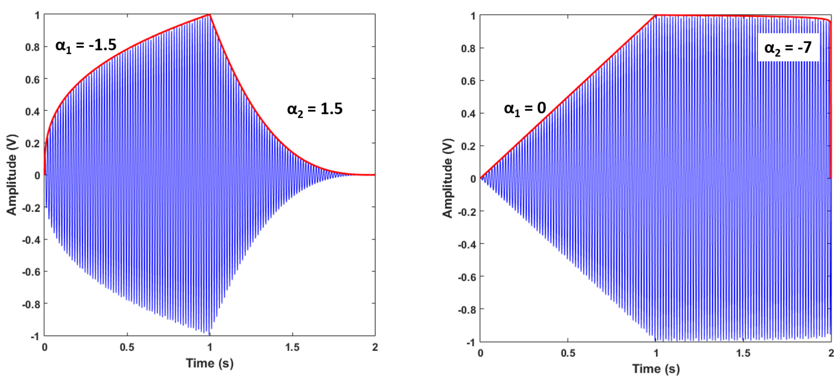


Figure 11: Two example single pulse stimuli created using the envelope parameter function shown in Figure 10 with parameter value α_1 for the increasing part and α_2 for the decreasing part.

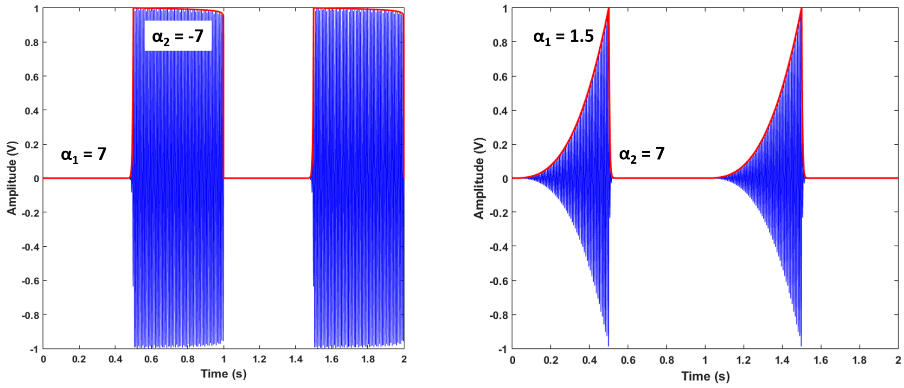


Figure 12: Two example double pulse stimuli created using the envelope parameter function shown in Figure 10 with parameter value α_1 for the increasing parts and α_2 for the decreasing parts.

A further set of stimuli were created in an additional attempt to cover the circumplex space. This contained 10 stimuli created in the same way as for the double pulse envelopes but using a random permutation of four α values, two for each pulse. This was in part to create greater variation of sensations in order to cover the space but also to investigate whether there is a relation between the response to a combination of two pulse waveforms and responses to each of those waveforms individually. For example, would two pleasant but qualitatively different waveforms combine to make an equally pleasant sensation or would it become unpleasant.

Finally, 6 further stimuli were added that were repeated copies of a single stimulus. These were to assess how consistent each participant was, particularly as the sensation of one stimulus could affect the perceived feel of the ensuing stimulus which could have a significant impact on the results. Having repeated stimuli would give an indication of the scale of this effect as well as a notion of how well tactile sensations are perceived. To enable direct comparison between participants, the same stimulus was repeated for each.

In total, a set of 108 stimuli was formed to present to participants. The experiment was carried out in an assigned room over the course of two weeks. It took approximately 20 minutes for a participant to run through all the stimuli while recording their responses and section breaks were put in to allow participants to pause if requested.

4.4 Experiment results

The data for each of the 20 participants from the experiment consisted of x and y mouse position values in the range [0,700] each for all 108 stimuli, as well as the stimuli name references. Upon first inspection of participant responses to the entire set of stimuli it can be seen that individuals vary greatly in their spread of reactions across the circumplex space. Figure 13 shows this with a sample of 6 participants chosen to demonstrate the range of responses. Participants 2 and 12 are particularly interesting since their results have very low variation in the Valence dimension. It was debated whether or not to remove these results from the data due to the extreme lack of variation in the valence direction. On the one hand their judgement that the stimuli were all pleasant in the case of participant 2 and neither pleasant or unpleasant in the case of participant 12 are valid responses that are important to take into consideration. However, their extremely low variation in Valence responses in comparison with the rest of the data could suggest a misunderstanding of the task and may limit the potential of finding significant correlations with this data. The participants could not be contacted to verify their understanding of the tasks. Therefore, calculations were done both with and without these two data sets and all presentations of data here include the two participants since significant results were found without excluding them.

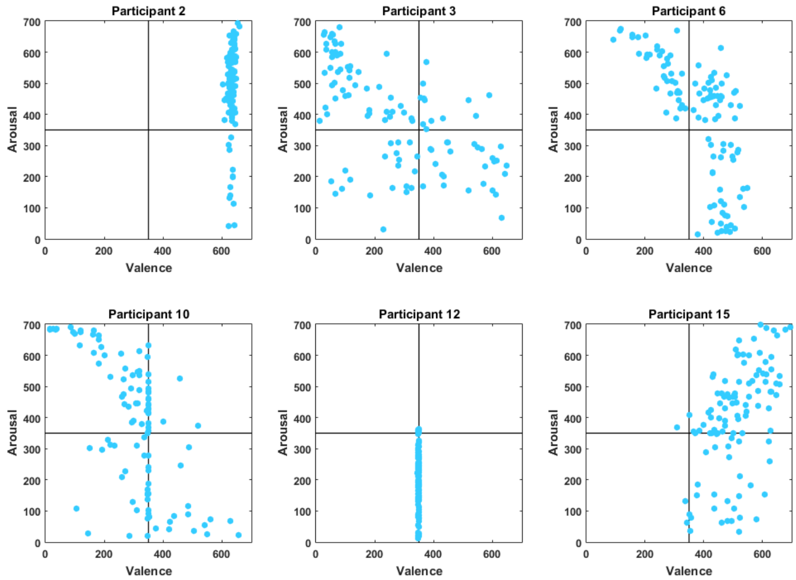


Figure 13: Results from 6 participants for perceived Arousal and Valence of all 108 stimuli to demonstrate the variation in results. All participant results shown in appendix

Figure 14 presents every result for every participant in which it can be seen that while there is variation between participants, overall the experiment succeeded in covering the space. The results in the negative quadrant are visibly less dense than in the other three but still contains data points across the full range. The challenge here is interpreting this correctly; it could suggest that stimuli were varied and inspired a full range of reactions, or it could be due to different participants having varied approaches to the task. Hence, the correlations between responses and stimuli features is key for finding consistencies between participants rather than focusing on the exact positions of responses in the space. Before further analysis was undertaken, all results were shifted and normalised to the scale [-1,1] for both Arousal and Valence.

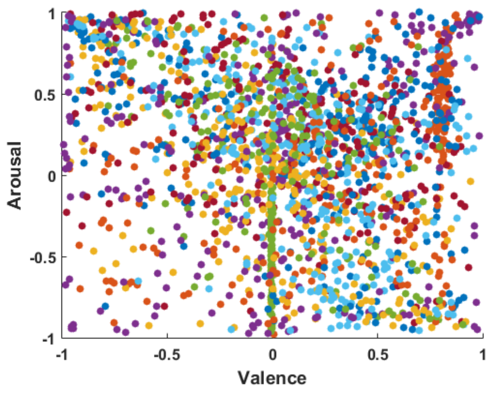


Figure 14: All results for all participants (defined by colour) to demonstrate the overall coverage of the space.

To ascertain the general skew of the data across stimuli, mean Arousal and Valence values for each stimuli were calculated and the Principal Component Vectors derived for this data set. The results of this are shown in Figure 15 where the first component vector is in the direction $y = -3.20x$ for y = Arousal and x = Valence. Immediately noticeable is that the general shape of this data including the principal components is very similar to the results of the VibViz experiment shown in Figure 7. The results from Suk et al presented in Figure 5 also match this trend. This suggests that there is generally a negative trend between perceived Valence and Arousal responses to tactile stimuli.

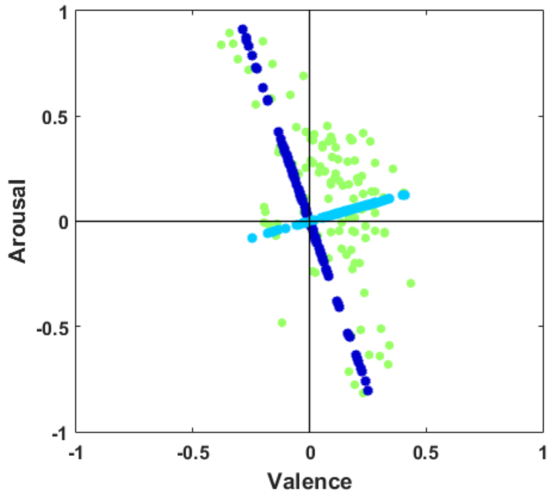


Figure 15: Mean Arousal and Valence data across participants (light green) projected onto the first (dark blue) and second (light blue) Principal Component vectors. The gradient of the first component vector is -3.20.

The graph in Figure 15 does not give any insight into the variation of responses to individual stimuli. The mean standard deviation across all stimuli for Valence was 0.23 (relating to an interval of 0.46 in the Valence dimension for 68% confidence) and for Arousal was 0.19 (relating to an interval of 0.38 in the Arousal dimension for 68% confidence). A confidence interval of 95% is defined by two standard deviations in either direction from the mean. The mean 95% confidence interval according to this rule was 0.92 in the Valence dimension and 0.76 in the Arousal dimension. This indicates 15% greater variance in a Valence response than an Arousal response to any given stimulus. It also suggests a high discrepancy between participant responses to specific stimuli.

Interpreting these values, this indicates that for any given stimulus, an area slightly smaller than one quadrant of the Circumplex Model can be marked for which we have 68.2% confidence that a user's response to the stimuli will fall into this area of the space. To demonstrate this visually, the responses of all participants to four individual stimuli are shown in Figure 16. The plots contain the responses to two sine and square wave stimuli at low frequencies of 2Hz and high frequencies of 64Hz. The mean across participants for each is shown by the large markers and the one standard deviation border is indicated for each by ellipses with principal axes defined by the standard deviation in the Arousal and Valence directions.

These plots suggest that square waves elicit higher Arousal responses and slightly lower Valence responses than sine waves. Mean results calculated for the whole data set of sine and square wave stimuli verify that this is the case as shown in Table 4. The mean difference between Arousal responses to square and sine waves across all relevant stimuli and all participants is 0.513. This means that on average square waves elicited an Arousal response over 25% greater than sine waves of equivalent frequency and amplitude. Calculating two standard deviations from the mean indicates that over 95% of the data concurs with the relationship that square waves elicit higher Arousal responses than sine waves. The converse was found for Valence responses with square waves eliciting a lower Valence response than sine waves for equivalent frequency and amplitude values. While the difference was smaller in this case, the standard deviation is also smaller and over 90% of the data concurs with the relationship. Therefore, it can be stated that square waves are generally considered more intense and less pleasant than sine waves. This could suggest that the qualitative sensations of a tactile stimulus have an impact on the response engendered. Or it may be due to the greater energy in square wave signals compared to sine waves.

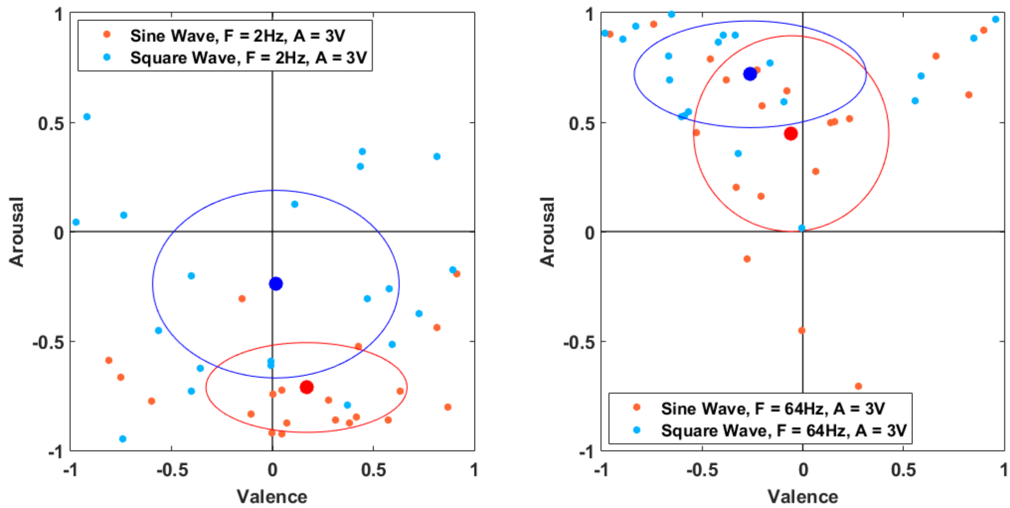


Figure 16: Results across participants for two Sine wave stimuli (light blue, mean across participants in dark blue) and two Square wave stimuli (light orange, mean across participants in red). The ellipses surrounding the means demonstrate the one standard deviation border.

	Mean across stimuli and participants	Standard Deviation
Arousal	0.513	0.242
Valence	-0.235	0.130

Table 4: Responses to square wave stimuli minus responses to respective sine wave stimuli, averaged across relevant stimuli and across all participants.

Additionally, it is clear for these stimuli in Figure 16 that Arousal is noticeably greater for the higher frequency stimuli. Figure 17 shows the raw correlation results across stimuli for every participant demonstrating the consistently high correlation between Arousal and frequency, including for participants 2 and 12. Correlations between the frequency of sine and square wave stimuli and the responses of participants are shown in Table 5 across all participants. For 21 stimuli - sine or square waves individually - the non-directional p-value for 95% significance is 0.432, and for 42 stimuli - both sine and square waves - the p-value is 0.304. The highlighted values in the table are significant by this definition. It can be seen then that there is significant evidence for a correlation between Arousal and the log of Frequency. Additionally, all the results for Arousal (excluding only square wave stimuli with 2V amplitudes) have a mean correlation value that is over two standard deviation distances from the threshold meaning that over 95% of the participant correlation results are significant.

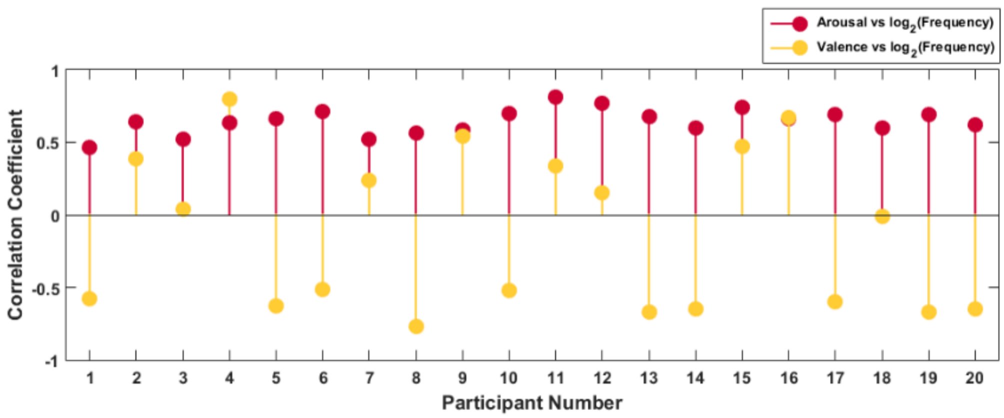


Figure 17: Correlation coefficients of Arousal and Valence against $log_2(F)$ (Stimuli frequency F = [2,4,8,16,32,64,128] Hz) across all sine and square wave stimuli for each participant.

Wave Type	Wave Amplitude (V)	Mean of participant correlations between $log_2(F)$ and Arousal	STD across participants
Sine Wave Stimuli	2	**0.807**	0.179
	3	**0.861**	0.077
	4	**0.875**	0.071
	2,3 and 4	**0.819**	0.077
Square Wave Stimuli	2	**0.585**	0.210
	3	**0.827**	0.122
	4	**0.828**	0.110
	2,3 and 4	**0.687**	0.100
Sine and Square Wave Stimuli	2,3 and 4	**0.675**	0.089

Wave Type	Wave Amplitude (V)	Mean of participant correlations between $log_2(F)$ and Valence	STD across participants
Sine Wave Stimuli	2	-0.033	0.649
	3	-0.256	0.660
	4	-0.188	0.699
	2,3 and 4	-0.166	0.584
Square Wave Stimuli	2	-0.076	0.612
	3	-0.109	0.741
	4	-0.236	0.683
	2,3 and 4	-0.128	0.574
Sine and Square Wave Stimuli	2,3 and 4	-0.131	0.541

Table 5: Mean and standard deviation results across participants of the correlation coefficients of $log_2(F)$ with Arousal (y coordinate of participant response) and Valence (x coordinate of participant response) where stimuli frequency F = [2,4,8,16,32,64,128] Hz. Including only the pure sine and square wave stimuli presented to participants.

Mean correlation values between Valence and frequency are all below the thresholds of significance, and have much greater variance between participants. However, many individual participant results are significant as can be seen in Figure 17. Of the 20 participants, 10 had significant negative correlations between their Valence responses and the Frequencies of the stimuli and 6 had significant positive correlation values. While the mean results are not significant, 80% of the participants having significant correlation values is a strong indication that stimulus frequency influences Valence response, but that the direction is subjective to the individual.

As well as frequency, the amplitude of the sine and square wave stimuli was varied. The calculated correlation coefficients for Arousal and Valence against amplitude are shown in Table 6. None of these results are above the significance threshold and the standard deviation values for the results are relatively low indicating that the majority of the correlation data is below the threshold. This is reflected in the individual participant results shown in Figure 18 where of the 20 participants, only 2 have a significant positive correlation value for Arousal against amplitude. The other 18 have lower but all positive values. Due to the consistency of sign, this could suggest that there is some form positive correlation between Arousal and amplitude or to some related feature of the stimuli. Further experimentation with a greater range of amplitudes and/or more participants would be necessary to counter or verify this suggestion. From this data alone, it is apparent that there is no significant relation between Arousal and the amplitude of tactile stimuli.

A similar result was found for the mean correlation between Valence and amplitude except the relation is negative. There is greater variance between participant results and a lower mean correlation result making it less likely that there is any general correlation between Valence and amplitude.

Wave Type	Mean of correlations between Amplitude (V) and Arousal across all participants	STD across participants	Mean of correlations between Amplitude (V) and Valence across all participants	STD across participants
Sine Wave Stimuli	0.171	0.125	-0.206	0.168
Square Wave Stimuli	0.299	0.14	-0.195	0.287
Sine and Square Wave Stimuli	0.203	0.092	-0.186	0.189

Table 6: Mean and standard deviation results across all participants for the coefficient of correlation between the amplitude of stimuli signals and participant Arousal (y coordinates) and Valence (x coordinates) responses. Using the pure sine and square wave stimuli for all frequency values.

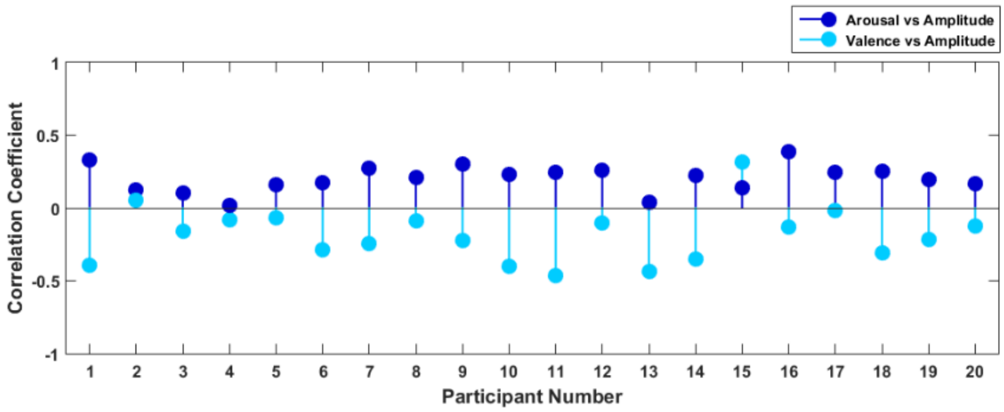


Figure 18: Showing the correlation coefficients of Arousal and Valence against Amplitude (V) across all sine and square wave stimuli for each participant.

Since the qualitative difference between sine and square waves was found to have an impact on participant responses, correlations with the α values of envelope waves were then calculated to get a better understanding of this relation. The results are shown in Table 7 for which the first two rows cover 25 stimuli and the bottom two rows cover 50 stimuli. The non-directional p-value for 95% significance is 0.396 for a sample size of 25 and 0.278 for a sample size of 50. The mean correlation values between α and Arousal are all negative, but only one result satisfies the threshold of significance. This value is within one standard deviation of the threshold suggesting that there was not a significant proportion of the data over the threshold. However, it still indicates a correlation between Arousal and the α values. The plots in Figure 19 show the waveforms for $\alpha_1 = \alpha_2$ in order of index 1 to 5 as they are referred to in Table 7.

In contrast, the Valence and α values appear to have no correlation, but a larger variance in results. Inspecting the correlation coefficients for each participant between $\alpha_1 = \alpha_2$ single pulse stimuli and Arousal or Valence, as shown in Figure 20, it is clear that although the sample size is small the correlation results are significant for certain individuals. While Arousal results are all negative bar participant 14, the Valence results vary with both positive and negative significant results. These results suggest a general negative relation between Arousal and α values, while the effect of α values on Valence responses is subjective according to the individual.

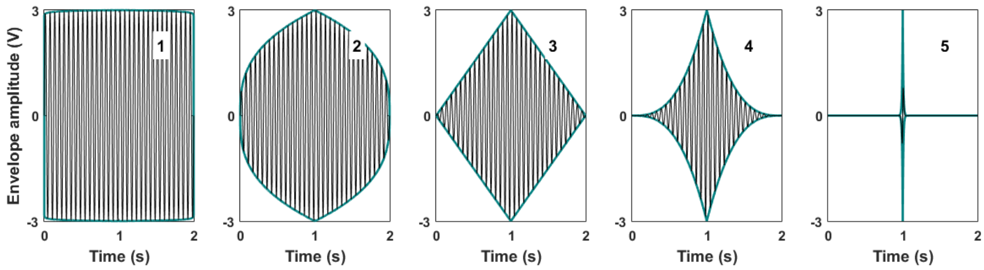


Figure 19: Demonstrating the waveforms for $\alpha_1 = \alpha_2$ in order of index 1 to 5.

α values	Mean of participant correlations between α and Arousal	STD across participants	Mean of participant correlations between α and Valence	STD across participants
α_1 fixed, α_2 increasing [1,2,3,4,5]	-0.3359	0.1422	0.0403	0.2675
α_2 fixed, α_2 increasing [1,2,3,4,5]	-0.3074	0.2115	-0.0810	0.3246
α_1 fixed, then α_2 fixed	**-0.3216**	0.1469	-0.0204	0.2735
$\alpha_1 = \alpha_2$ for both single and double pulse stimuli	-0.2532	0.2578	-0.0011	0.3318

Table 7: Mean and standard deviation results across all participants for the coefficient of correlation between α values of envelope stimuli and participant Arousal (y coordinates) and Valence (x coordinates) responses. Includes correlations with α_1 and α_2 separately and together.

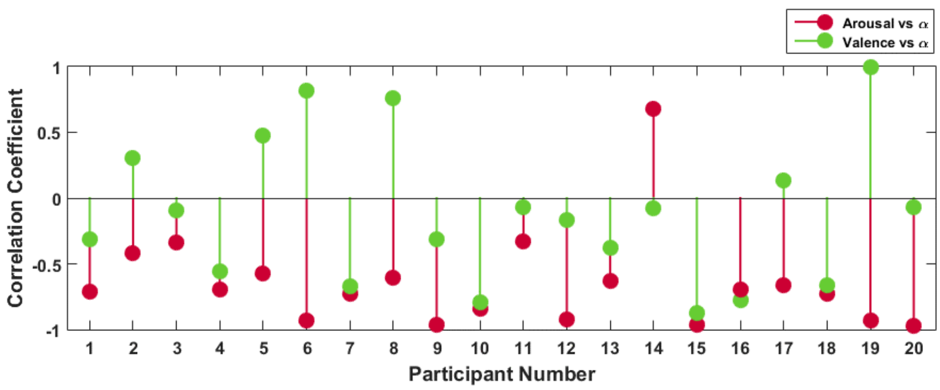


Figure 20: Correlation coefficients of Arousal and Valence against $\alpha_1 = \alpha_2$ values.

It was expected that as the index increased, Arousal responses would increase since the waveform shape gets 'sharper'. However, the opposite was found. This could be that the amount of energy in a signal is affecting the response, since the energy in the signal decreases as the index of α increases. This would concur with the results of the VibViz data as well as the difference between Arousal responses to sine and square waves. To test this, the mean and total energy in stimuli signals were calculated and the correlation found between these and Arousal and Valence. The results were similar for both. Correlations with total energy only are displayed in Table 8 where the p-value thresholds of 95% significance are 0.278 for the sample of 50 envelope waves, 0.304 for the sample of 42 sine and square waves, and 0.189 for all 108 stimuli. All results for Arousal are above the respective thresholds, as highlighted. However, they are all within one standard deviation of the threshold meaning that less than 85% of the participant results were significant. Inspecting the individual participants, 8 of the 20 had significant correlations between Arousal and energy, while 11 had positive correlation values that were less than the threshold of significance. This indicates a positive relation between energy in the stimuli and Arousal, but since the majority of participant results are not significant this correlation can not be generalised.

The converse was found for correlations between total signal energy and Valence; only one mean result is significant and the variance is high across participants, so it appears that there is no correlation between signal energy and Valence. Yet, 14 of the 20 participants had significant correlation results, 12 of which were negative, suggesting that signal energy did have an effect on Valence responses in certain individuals.

	Mean of participant correlations with Arousal and total energy in stimuli	STD across participants	Mean of participant correlations with Valence and total energy in stimuli	STD across participants
Envelope wave stimuli only	**0.3916**	0.1743	-0.0305	0.3726
Sine and square wave stimuli only	**0.3965**	0.1064	-0.2539	0.2631
All stimuli	**0.2081**	0.1368	**-0.2093**	0.2471

Table 8: Mean and standard deviation results across all participants for the coefficient of correlation between mean and total energy values of envelope stimuli and participant Arousal (y coordinates) and Valence (x coordinates) responses.

An important aspect of the experiment results not yet discussed is how effectively participants were able to differentiate between tactile stimuli. The 6 repeated stimuli were included in the experiment for this purpose. The Arousal and Valence responses for all participants to these repeated stimuli are shown in Figure 21 where it can be seen in the left panel that the results across participants are spread across all four quadrants of the space. On first inspection this suggests that participant responses are very inconsistent. However, the mean position in the space across participants is similar for each presentation and the results of each stimulus presentation for individual participants have a much lower variance as shown in the right panel.

The standard deviation of responses per participant varied between 0.0050 and 0.3622 with the mean standard deviation in the Arousal direction of 0.167 and the mean in the Valence direction of 0.148 as shown in Table 9. To indicate whether the STD is significant for each participant the percentage of total Valence and Arousal STD was also calculated. The standard deviation is slightly larger in the Arousal direction but more consistent across participants whereas the standard deviation in the Valence direction varies more among participants but for some is very low indicating that some individuals were much more consistent in their judgement of how pleasant a stimulus was than others.

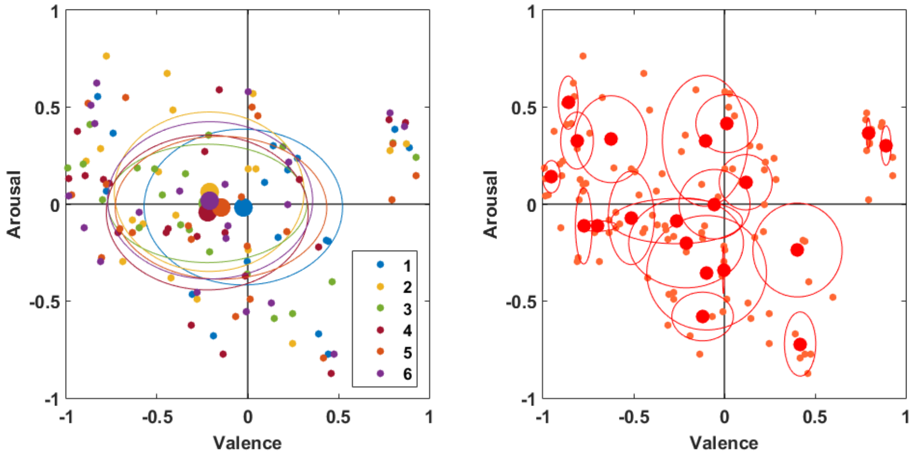


Figure 21: Left: Results of all participants for the 6 repeated stimuli (1-6 in order of presentation to each participant) with the mean result across participants indicated by the large markers, including one standard deviation border for each. Right: Small markers present the results of all participants, large markers present the mean result for each individual participant across all 6 stimuli including the one standard deviation border.

	STD of Arousal scores for each participant		As a % of total STD of Arousal across all stimuli and each participant		STD of Valence scores for each participant		% of total STD of Valence scores for all stimuli and each participant	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Across the 6 repeated stimuli	0.167	0.077	35.6	15.9	0.148	0.108	49.3	43.1

Table 9: Mean and STD across participants of the STD for individual participant Valence and Arousal scores across 6 repeated stimuli. Percentage of total Valence and Arousal STD also included.

From these mean standard deviation values, to have 95% confidence in an individual's response to a single stimulus would require identifying an area that covers 15.5% of the circumplex space. To understand the meaning of this in comparison to participants choosing the points at random, a simulation of 20 participants choosing 6 random locations in the circumplex space was run in Matlab utilising the inbuilt random number generator. The mean standard deviation result was 0.5793 in the Arousal direction and 0.5391 in the Valence direction. For a 95% confidence in one of these simulated individual's response 98% of the circumplex space would need to be covered. Therefore it is clear that the participants were not choosing at random, and this result indicates that they were generally reliable as individuals. The results also verify that participant results should not be compared directly since Arousal and Valence responses to tactile stimuli are subjective.

4.5 Comments and limitations

None of the expected relationships were found for the envelope stimuli generated with randomised orders. This data was not included as the stimuli were too limited and varied to give clear conclusions.

In the experiment a number of comments were made by made by participants during the informal feedback session offered at the end of each experiment that the numerous stimuli presented to such a localised area on the fingertip affected their perception of the sensations and meant they were less able to differentiate sensations after many presentations. Some participants also commented that it was challenging to rate their pleasantness responses since there was no defined scope to compare them to. Despite these comments, clear correlations were found in the data that are significant at a 95% level. The data is limited by only having 20 participants but engenders a better understanding of our general perception of localised tactile stimuli.

5 Hardware experimentation

Having investigated which features of haptic sensations affect the emotional responses elicited in participants, we were in a good position to trial mappings between music and tactile sensation. This involved the design, fabrication and then testing of a prototype for a wearable device capable of generating more complex sensation combinations and compositions than experienced above. Initial questions included what form of tactile interface to use, where it should be positioned on the user's body and what size it should be. Limiting factors included the resources available and the practicalities of creating a prototype that could generate a sufficient variety of sensations within the project timescale. The end result had to be adaptable and easy to use.

5.1 Prototype design

Tactile sensations that could have been created by the device included stroking, squeezing, tickling, spiking, vibrating and tapping. There were many potential methods for creating these sensations. Servo motors were considered as a means to generate stroking and tapping sensations. A blood pressure sleeve attached to a motored air pump was tested as a method of squeezing. Pager and pancake vibration motors were tested to create vibrating and tickling sensations, as well as spiking sensations by attaching 3D printed casings with textured surfaces as shown in Figure 22. The tactors from Experiment 1 were also considered for creating vibrations but the sensations were difficult to distinguish on areas of skin less sensitive than the fingertip. A TENS machine (utilises transcutaneous electrical nerve stimulation typically used for pain relief) was trialled as a means to engender more unusual tingling sensations.

The vibration motors were the most practical being small, cheap and capable of creating a variety of sensations by altering the intensity and position of vibration in multiple motors placed across the skin. It was found that more sensations were possible than previously considered using these; tapping effects were created by processing the running voltage with a square waveform and stroking/tickling sensations were attempted by running a series of motors in sequence across the skin with low intensity. An arm squeezer was effective as a means to generate low frequency pulses and straight forward to create by removing the sleeve of a blood pressure monitor then attaching the input tube to an air pump. When the motor pumped up the sleeve it generated vibrations through the device that could be felt as well as the variations in pressure. As well as pulsing the squeezer had potential to build tension or drama in a piece by gradually increasing the pressure over a longer time period.

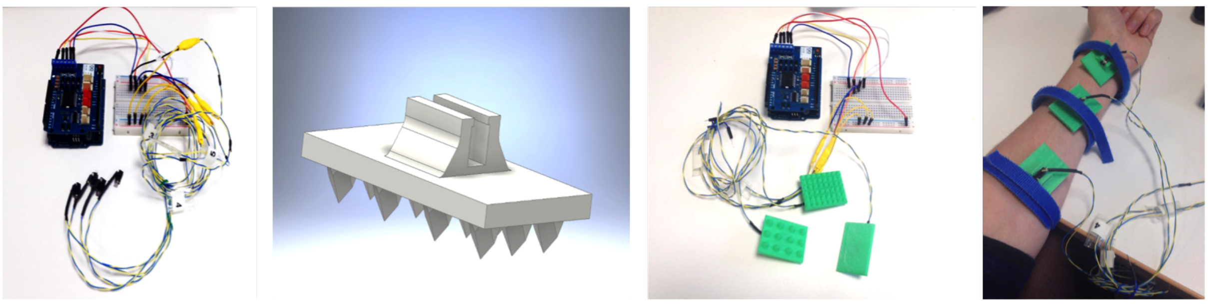


Figure 22: Left to right: First tests using four pager motors via a single Arduino Uno board. Example design for a 3D printed motor casing with spiky surface. Set up for testing three different casings. Initial tests of motors with casings on a user's forearm.

While various positions and combinations were possible, through discussions and demonstrations with users, it became apparent that the most effective and practical area was the forearm. The forearm is easily accessible and users reportedly felt at ease wearing the device there, whereas a vest or device worn on the neck or ankles would have made some users uncomfortable and would make it challenging to create a device compatible with all users. While not as sensitive as the hand, users could differentiate the locations and intensity of sensations created. It also left the user's hand free to move so that the device did not limit the ability of users to carry out tasks such as typing or writing.

The final prototype as shown in Figure 23 was formed of an Arduino Leonardo board with three stacked Motor Shields, each with jumpers soldered to set a unique hardware address, from which eight vibration motors and one vacuum pump were run. The vibration motors were wired up then encased in short lengths of 1cm diameter plastic tubing to prevent any obstructions to the motor rotation. A material wrap-around sleeve was made with an array of pockets sewn on to hold the motors. This allowed the motors to be placed in a multitude of arrangements within the sleeve such as spiralling around the forearm, in successive pairs or in one ordered line down the forearm. For the final experiment they were placed and kept in an ordered line since it proved to be challenging to change the arrangement in the middle of each participant run and ensure consistency. The squeezer, connected to the vacuum pump, was wrapped around the upper arm just above the elbow so there was minimal space between the squeezer and the motors giving an impression of wearing a single connected sleeve.

Figure 23: Photos of the final prototype. Left: All components of the final device. Middle top: Motor before and after wiring and casing. Middle bottom: Stacked Arduino shields. Right: The device worn by a participant.

5.2 Implementing tactile compositions onto prototype

The role of the Arduino was to set the speed of each motor thereby generating the desired intensity or pressure at a given time. For each time step of 10ms, the Arduino set the speed of the eight motors and the vacuum pump to specific input values scaled to the interval [0,255] where 255 was the maximum speed. Initially the Arduino was run via serial from Matlab. The program sent details of the voltage output desired for each motor on each 10ms time step. However, the serial connection introduced delays that were difficult to measure accurately and did not appear to be consistent. Therefore, a different approach was utilised whereby the desired motor outputs over a given time were written to a text file as an array of numbers. This was saved on a micro SD card shield attached to the ICSP pins of the Leonardo board. When commanded to start, the Arduino would then read a line of values directly from the relevant text file and use them to update the motor speeds on every time step. This was faster and more consistent, allowing all delays to be managed by the Arduino. Limitations to this method included the inability once started of the Arduino to pause or restart a piece and that new pieces had to be manually saved onto the SD card and the name written into the program.

6 Experiment 2

Having designed and created the prototype the next phase was to assess how effective it was at creating experiences that evoked emotions in the user. Although primarily aimed at an audience with hearing impairment the device could also be used to enhance music for those able of hearing. The experiment was designed to test how well it worked in three different situations; as a replacement for music, as an enhancer of music or as a whole new sensory medium. Therefore, participants were given a range of stimuli to rate that included music samples, tactile compositions and tactile sensations mapped from the music samples that were played both with and without the music. They were asked to score their impressions each time to give an idea of how enjoyable the device was to use.

6.1 Experiment setup

Due to time limitations this experiment was kept short so that the focus could be put on creating interesting stimuli rather than large numbers of stimuli. Undertaken in a quiet setting, the participants were given over-ear headphones and asked to use a laptop and mouse to rank the sensations they felt or heard via an interactive questionnaire. The device was worn on the non-dominant arm and participants were given three test samples before being presented with stimuli to introduce them to the sensations created by the device. They were asked to wear the the headphones throughout the experiment even when only tactile stimuli were presented in order to block the sound of the motors. Instead of using the full circumplex space only Valence was measured. This was to focus the analysis since the device and stimuli were more complex. For each stimulus, participants were asked to rate the sound or sensation on an integer scale of [-5,5] where -5 represented 'Very Unpleasant', 0 represented 'Neutral' and 5 represented 'Very Pleasant', a variation of the Likert scale. Stimuli were presented in three blocks; music only, tactile only and then combinations of music and tactile. The stimuli in each block were in a randomised order for each participant.

6.2 Participants

There were 20 participants in total, all had dominant right hands for using a computer mouse. Of these 20 participants, 9 were female and 11 were male. The age range consisted of 9 participants in the age bracket [20,30] years, 2 in [30,40], 2 in [40,50], 1 in [50,60] and 6 in [60,70].

6.3 Experiment stimuli

This part of the project was mainly focused on what sensations could be created with the prototype device to give users a range of experience. It was an opportunity to be creative with the model and explore the feasibility of mapping music into the haptic domain. As discussed, the stimuli needed to allow for comparison of tactile sensations as independent experiences as well as for enhancing or replacing music. The stimuli for this experiment were more challenging to create than before since greater complexity in the dynamics and sensations was desired and the output required specific formatting to be put onto the SD card then read by the Arduino. In total 28 stimuli were presented to participants, which were split into four groups. The first group was a set of 7 music samples ranging from 14 to 42 seconds in length. We label this group M1,...,M7. Two of these were simple chord progressions in major and minor keys, then the other five were instrumental samples taken from five songs of varying genre and popularity. The songs were 'Ashes to Ashes' by David Bowie; 'Soul Bossa Nova' by Quincy Jones; 'Main title and first victim' (Jaws themetune) by John Williams; 'Is this Love' by Bob Marley and 'Sweet Sixteen' by BB King. These were chosen to have clear rhythms or melodies to map onto tactile sensations.

The second group of stimuli were eight different tactile sensation combinations composed by hand for the prototype device. These included having different combinations of varying both the intensity and position of the vibration and creating patterns of vibration across the forearm. They are labelled S1,...,S8 discussed further in Section 6.3.1.

The third group was also formed of purely tactile sensations, but this time the sensations were designed to match or counter the music samples in the first group. The mappings for these stimuli were created by converting the music samples to midi files and extracting information that could be mapped into vibration such as the notes, rhythms and frequencies contained in each piece. These are labelled T1,...,T7 and are discussed further in Section 6.3.2.

The fourth and final set of stimuli were presentations of the music samples from the first set together with their respective tactile mappings in the third set to see how the response of participants to the combined sensation differed to experiencing them separately. These combination stimuli are labelled C1,...,C7. It was necessary to have this set of stimuli at the end of the experiment so that participants gave an unbiased opinion of the music and tactile mappings separately without any association between them before experiencing the combination. The BB King track in this set was played with a random pattern of vibration that was not related to the music sample to see if there was a contrast in how this was perceived.

6.3.1 Tactile stimuli

The first group of tactile stimuli, S1 to S8,were created with an aim to explore the variety of sensations that could be generated with the prototype. The parameters that could be changed for the motors were the intensity of the vibrations, position of the vibrations and the combination of motors running at any given time. For the squeezer, only the pressure could be varied and this was limited due to requiring an average pressure over time equal to that generated by 65% of the maximum vacuum pump motor speed. The value of 65% related to the Arduino setting the output speed of the motor to 166 which was found to stabilise the pressure at 40 mmHg; a comfortable level. It was apparent through testing that the squeezer had a marked delay between increasing the motor speed and the pressure increasing. Therefore any rhythm or pulsing desired from the squeezer was generated with square waveforms to get the fastest reaction time possible and frequency was generally capped at 2Hz. The layout of the motors in the experiment was in an ordered line from 1 to 8 along the length of a participant's forearm so these stimuli were created with this format in mind.

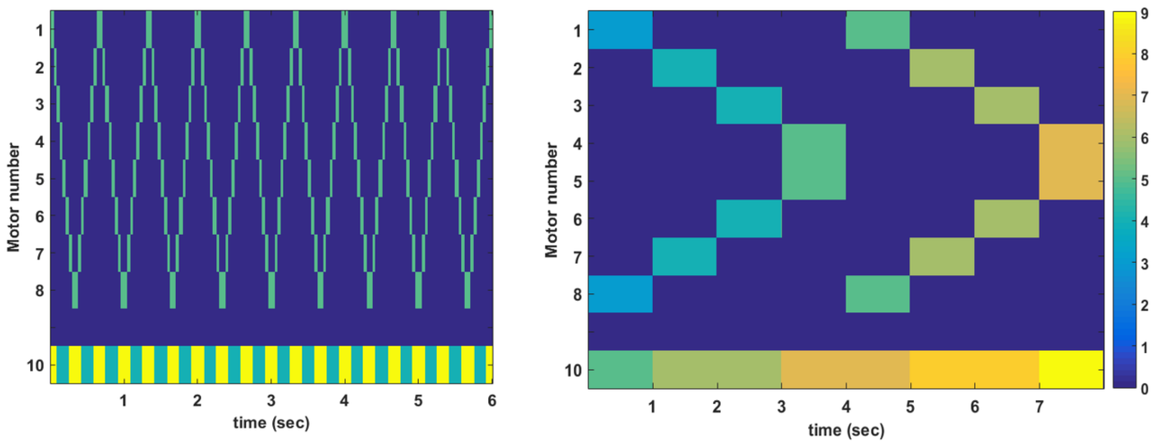


Figure 24: Examples of two tactile stimuli generated for motors 1 to 8 and squeezer labelled 10. Left: Sawtooth progression of motors with squeezer pulsing on minima and maxima (S1). Right: Progression on pairs of motors from outside to inside with increasing squeezer pressure (S4). The colour bar indicates motor intensity where 9 represents 90% of maximum intensity and 0 is off.

Stimuli S1 to S3 were variations on a sawtooth waveform travelling up and down the arm. This was generated by shifting and scaling a sawtooth wave to lie in the amplitude interval [0.5,8.5] then rounding the value of this waveform for each time step to get an integer in the interval [1,8] indicating which motor to switch on at that time. The sawtooth waveform was chosen as it created the best effect of the sensation travelling up and down the arm simulating a rhythm. A pulsed rhythm was included via the squeezer by generating square waveforms shifted to have an average amplitude equivalent to 65% motor speed. Stimulus S4 also utilised a sawtooth wave but this time to determine the intensity of all the motors in unison, rather than the motor number to switch on as shown in Figure 24.

Stimuli S5 to S8 were less similar. Stimulus S5 was created by switching the motors individually on and off for random time intervals utilising Matlab's randi function. The squeezer also pulsed for random intervals, but they were altered to ensure that the average remained consistent at 65% of maximum power as discussed previously. Stimulus S6 treated the motors as 4 pairs of 2 neighbouring motors and was generated by cycling through the pairs, switching them on for 1 second intervals with increasing intensity levels as shown in Figure 24 Bottom Right panel. The squeezer increased pressure gradually to match the increase in intensity of the motors. Stimulus S8 was a similar progression of pairs, this time matched from the outside to the middle so motors 1 and 8 were paired together, motors 2 and 7 were together and so on. For this the squeezer pulsed on each change of pair while the motors increased in intensity over time.

There were many more options available and these stimuli did not completely represent the range of sensations possible. However, they gave an indication of the feasible sensation combinations and with the time limitations at this point the focus was put into the musical mappings over creating more of these stimuli.

6.3.2 Musical mappings

For the first six music stimuli M1 to M6, mappings were made from their midi files onto patterns of intensity on the motors and squeezer. The seventh music sample was played with an unrelated random arrangement of vibrations for comparison with the matched patterns. Firstly the midi files were generated from the original mp3 files using an online converter. A package [39] was used to read the midi file into Matlab allowing the extraction of note frequency and timings from each sample. Every song was different and mappings were made by manually selecting the features from the array of notes, assigning them to the motors with a chosen intensity then testing them on the device and modifying the mapping if necessary. It would be possible to automate this process once a mapping algorithm was formalised.

An example of this mapping is shown in Figure 25 for the 'Ashes to Ashes' instrumental sample. The top panel contains a small segment of the overall array of notes in the midi file for which note number 70 relates to middle C. This was inspected while listening to the song to determine which elements of the matrix represented the melody and which rhythms or other features were most apparent. While it varied between the different song samples, the general method was as follows. First a row or multiple row sections were chosen that contained a fundamental bass rhythm that could be implemented onto the squeezer. Since the midi file output was 100 samples per second, it was convenient to use a 10ms time step so that values could be mapped directly. Therefore, the values in the chosen rows were saved in a vector of length 100 multiplied by the sample time in seconds. They were then shifted and scaled to have an appropriate spread around a mean of 6.5 to represent 65% power to the vacuum pump and constant pressure on the squeezer.

Secondly, the key melody was identified and mapped onto the motors by assigning a note to each motor in order of pitch. If the melody had fewer individual notes than eight, it was possible to map directly and attempt to get an accurate representation of the difference in pitch by altering the spacing between motors chosen. However, if there were more notes or greater variation in the pitches than 8 motors could represent this was more challenging and had to be adapted. For the example in Figure 25 the main melody in the first 30 seconds was mapped onto four motors 2-5, allowing for further high frequency rhythms to be represented on motors 7-8 with a physical gap to differentiate them (motor 6 was not used). These extra rhythms were given lower intensity values than the melody as it was found that having too many features represented with high intensity made it difficult to distinguish between them and users found the high frequency rhythms uncomfortable if the power to the motors was too high. The values in the specific rows were put into vectors for each motor. All of these combined with the squeezer values formed an array of intensities for each time step that could be saved to a text file and used by the Arduino.

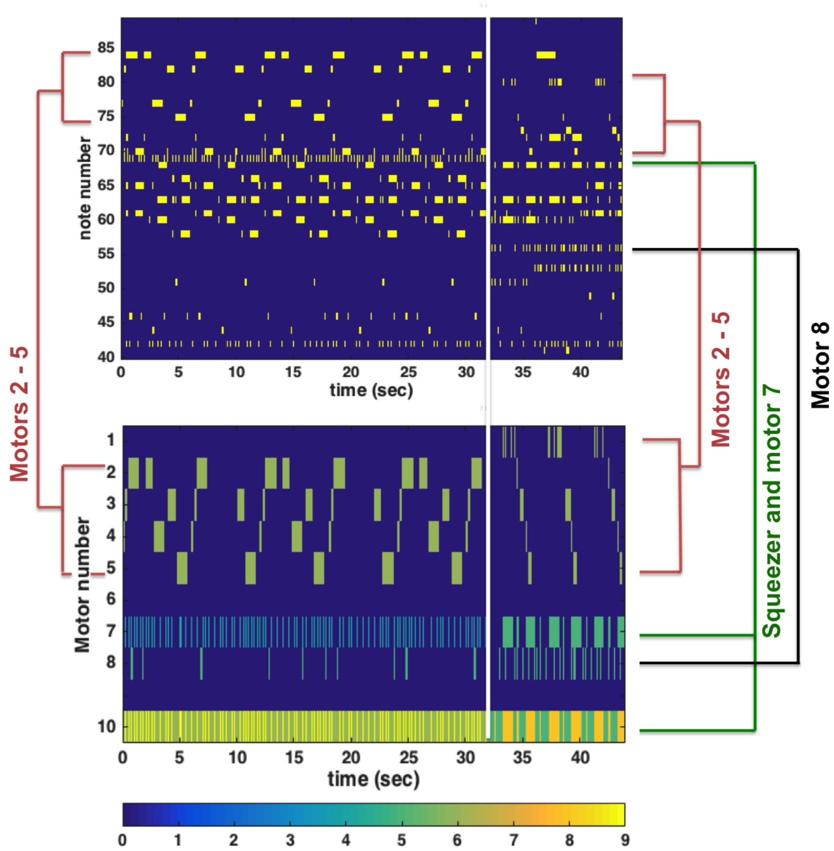


Figure 25: Demonstration of mapping between the extracted notes from the midi file for the 'Ashes to ashes' instrumental sample. Top panel: Section of extracted notes from original midi file. Bottom panel: The tactile mapping for this sample. Colour indicates intensity for motors 1-8, 1 being closest to the wrist and 8 closest to the elbow, and the squeezer labelled 10. The white line separates a natural transition in the music that was reflected by altering the mapping between the two sections.

The main technical challenge in setting up the experiment was in automating a system capable of playing music through the laptop in sync with the tactile sensations through the Arduino circuit. Before the experiment could be carried out, tests were undertaken to measure the delays in each part of the system and then minimise the error between audio and tactile playback. This was not important for the stimuli that only played through one medium, but for the music samples with tailored tactile compositions it was very important that the two were in sync or this had a great effect on the user response. A piece of music played out of rhythm with the vibration patterns was dramatically different to the experience of them both when in sync with one another.

While this could not be completely overcome since Matlab varied slightly in the execution time for each individual function, a number of fixes were made to obtain the closest match possible. By timing the Arduino code from receiving the serial start command to the end of playing a piece of known length, the offset was calculated and taken off each time step. This meant that a 10ms time step was actually specified as 3.83ms to account for the delay in running the program. Also, the Matlab functions were prepared such that all the variables were ready in the workspace prior to sending the start command to the Arduino via serial. The mp3 file of the music sample was played before this command was sent including a 23ms delay to allow time for the start command to reach the Arduino and for it to begin.

6.4 Change in experiment design

After eight participants were tested it was clear that the data gathered was not informative enough to draw statistically significant conclusions. While there was a change in response between hearing music only and when combined with tactile sensations, there was no significant correlation evident within or across participants so more information was needed. Through discussions with participants post-experiment and analysing the results up to that point it was apparent that 'pleasantness' was interpreted differently by each participant, particularly with the tactile sensations for which many were unsure of how to rate their response if they considered a sensation to be interesting or coordinated with the music but not necessarily pleasant. For example the 'Jaws' theme tune was reportedly dramatic and tense but not necessarily pleasant or unpleasant.

This led to a modification of the experiment with the aim to improve understanding of the results. All subsequent participants were played the same stimuli as before and responded using the same ranking, but were then asked to give three adjectives that best described the stimuli presented. These were chosen from a specified list created using Hevner's adjective circle [19] from Figure 1a. The circle contains eight groups of adjectives specific to emotions evoked by music. Although the original circle has varied group sizes, only six words from each group were used here to avoid any choice bias. These are shown in Table 10 in their eight groupings.

I	II	III	IV	V	VI	VII	VIII
Serious	Sad	Sentimental	Lyrical	Playful	Happy	Exhilarated	Vigourous
Dignified	Melancholy	Tender	Leisurely	Humorous	Joyous	Dramatic	Robust
Lofty	Depressing	Dreamy	Satisfying	Sprightly	Gay	Passionate	Emphatic
Sober	Heavy	Longing	Tranquil	Light	Merry	Exciting	Ponderous
Solemn	Tragic	Yearning	Quiet	Delicate	Cheerful	Restless	Majestic
Spiritual	Dark	Pleading	Soothing	Whimsical	Bright	Triumphant	Exalting

Table 10: The eight groups of adjectives presented to participants in the final experiment, taken from Hevner's adjective circle. [19]

There is no quantifiable measure of affective distance between the groups of words, but they are ordered such that neighbouring groups are related. The participants were presented with the adjectives in a randomised, unbiased order. Therefore, initial analysis would be to inspect the how many words chosen to describe a stimulus were of the same group and whether this was consistent across all types of stimuli. Another pattern to analyse would be how the response of participants differs between hearing a song and feeling the tactile mapping of that song. If the descriptors chosen fell into the same group for both then this could suggest that the tactile mapping has succeeding in presenting the general atmosphere of the piece, even if their pleasantness rankings differed.

6.5 Experiment results

The main data set was the pleasantness rankings since these were available for all 20 participants. The mean results across the music only (M1 - M7), tactile only (T1 - T7) and combined (C1 - C7) stimuli are shown in Figure 26. The mean across all participants is 0.3671 for stimuli M1 - M7, 0.1214 for stimuli T1 - T7 and 0.3771 for stimuli C1 - C7. This indicates that tactile sensations are generally found to be less pleasant than the music stimuli. The similarity in the mean responses to music and to combined stimuli could suggest that participants either ignore the tactile sensations and tend to rank just the music when presented with both, or that the combination of the two improved their perception of the tactile sensations.

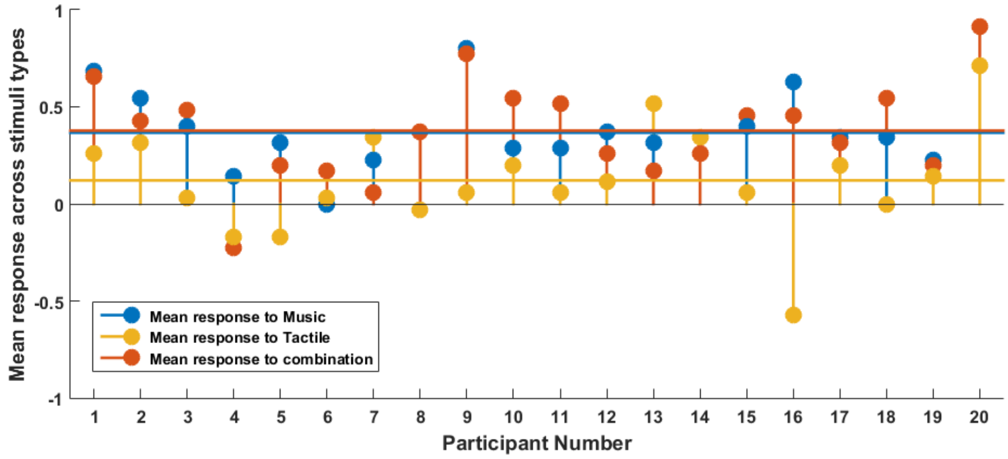


Figure 26: Mean normalised pleasantness response (-1 unpleasant to 1 pleasant) of each participant across the music stimuli (M1 - M7), tactile stimuli (T1 - T7) and combined stimuli (C1 - C7). Including means across all participants indicated with horizontal lines.

Null hypothesis H_0	T-test result at 5% significance level
M = T	Reject H_0 (M>T)
M = C	**Accept** H_0
T = C	Reject H_0 (C>T)

Table 11: Results of a paired t-test on response results per song sample for sets; M: Music only stimuli results across participants. T: Tactile only stimuli results across participants. C: Combined music and tactile stimuli results across participants. Accepting the null hypothesis indicates that two sets are statistically similar.

To assess the significance of these differences a pairwise T-test was carried out to compare the sets of responses for Music, Tactile and Combination stimuli. The T-test assesses the null hypothesis that two sets are significantly similar by giving a test statistic of whether the difference in the two sets comes from a normal distribution with mean zero. A 5% significance level was used meaning a 0.95 probability in the result. The results are shown in Table 11 where it can be seen that the responses to Tactile only stimuli (T) are statistically different to the responses to Music (M) and Combination (C) stimuli, whereas these two are statistically similar. The difference between Tactile only and Music only stimuli indicates that the mappings were not effective at eliciting the same response from the user as the respective song sample. However, the differences in responses to individual song samples needs to be investigated to verify or counter this.

To observe these effects for each individual music sample 1-7, the mean responses across participants per song were calculated as shown in Figure 27. The error bars represent one standard deviation distance from the mean. T-test results comparing the Music only (M), Tactile only (T) and Combination (C) presentations of each song sample are shown in Table 11. Looking at the graph, the mean results appear similar across the music, tactile and combination presentations for each song. However, the t-test results demonstrate that many of the results are in fact statistically different. In 4 of 7 stimuli, the responses to Tactile only presentations were statistically different to the responses to Combined presentations. And in 3 of the 7 stimuli, results between Music only and Tactile only presentations of the song samples are statistically different. The latter result is particularly interesting since it transpires that 4 of the 6 tactile stimuli designed to match the music (not counting T7 as it was randomly generated) have elicited responses statistically similar to the responses engendered by the respective music samples. This implies that the mappings were mostly effective at eliciting the same response as the music. In addition to this, the t-test results indicate that responses to the music sample M7 are statistically different to the responses elicited by the respective tactile stimulus T7 which was not mapped from the music. While one stimulus is too small a sample to draw conclusions from, this is a positive result as it suggests that the tactile mappings generally did better than a random stimulus at eliciting the same response in the user as elicited by the music. Further experimentation would be necessary to verify these findings.

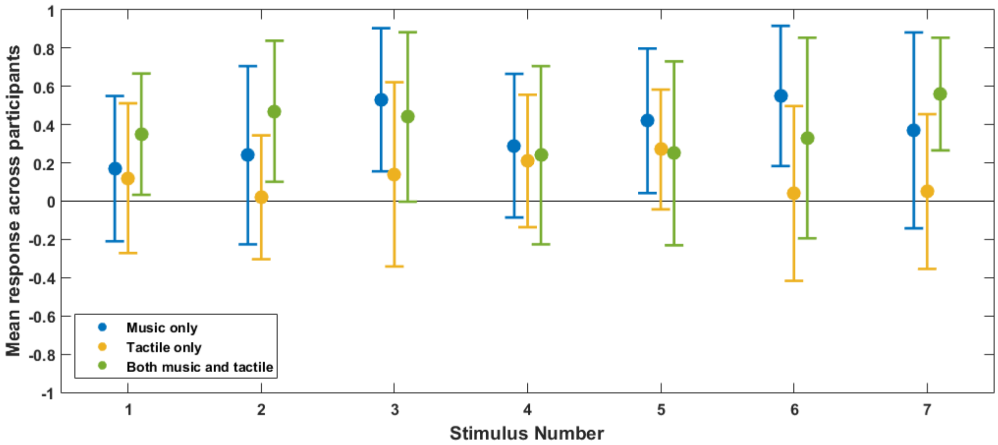


Figure 27: Mean normalised pleasantness response (-1 unpleasant to 1 pleasant) across all participants for each of the 7 music stimuli, equivalent tactile stimuli and combined stimuli; 1: Major chord progression. 2: Minor chord progression. 3: 'Ashes to ashes' instrumental. 4: 'Soul bossa nova' introduction. 5: 'Jaws' theme tune. 6: 'Is this love' instrumental. 7: 'Sweet sixteen' instrumental. Error bars indicate 1 standard deviation either side of the mean.

	T-test result at 5% significance level for stimulus number:						
Null hypothesis H_0	1	2	3	4	5	6	7
M = T	**Accept** H_0	**Accept** H_0	Reject H_0	**Accept** H_0	**Accept** H_0	Reject H_0	Reject H_0
M = C	**Accept** H_0	Reject H_0	**Accept** H_0	**Accept** H_0	**Accept** H_0	**Accept** H_0	**Accept** H_0
T = C	Reject H_0	Reject H_0	Reject H_0	**Accept** H_0	**Accept** H_0	**Accept** H_0	Reject H_0

Table 12: Results of a paired t-test on sets M: Music only stimuli results per stimuli across participants. T: Tactile only stimuli results per stimuli across participants. C: Combined music and tactile stimuli results per stimuli across participants.

For 6 of the 7 song samples, the responses to Music only and Combination stimuli were statistically similar, indicating that participants' responses to music were generally unchanged by the addition of tactile sensations. This could suggest that since the tactile stimuli match the music, the combination of the two did not change the response to either. However, more than half of the responses to Tactile stimuli alone were statistically different to the Combination stimuli. As well as this, responses to M7 and C7 were statistically similar despite the fact that the tactile stimulus was not mapped from the music. Therefore, it is more likely that when presented with a Combination stimulus, participants were ranking the music more than the tactile sensations. A few participants commented that for the Combination stimuli they generally focussed on the music, which concurs with these results.

Despite the statistical difference in many of the results, it is clear that the majority of responses lie in the positive half of the pleasantness space. In addition to this, the standard deviation is reasonably large for all of the results and not significantly greater for any particular stimulus type. Similar to the findings in Experiment 1 this suggests that Valence responses vary widely across participants. To get a better understanding of this further experimentation would be necessary utilising a wider range of stimuli and greater attempts to create tactile sensations that do not match a piece of music. For example, song sample 7 was upbeat, which may in some way have matched the randomly changing vibrations despite not being in sync with the music. A serene, tranquil song played alongside a tactile composition of very forceful rhythms and intense vibrations may induce a more dramatic difference in response. This form of sensory discordance requires further study.

As found in Sections 2.2 and 2.3, an individual's background and musical training affects their understanding and response to a musical piece as does their taste in genre. While no information on musical background was gathered on the participants, their ages were spread with 9 in the youngest age bracket [20,30] years and 6 in the oldest age bracket [60,70]. Age could have an influence on both their taste in music and sensitivity to tactile stimuli. To investigate this, the 6 oldest participants' responses were compared with the 6 youngest participants' responses. Mean responses across each participant group for all stimuli are shown in Figure 28.

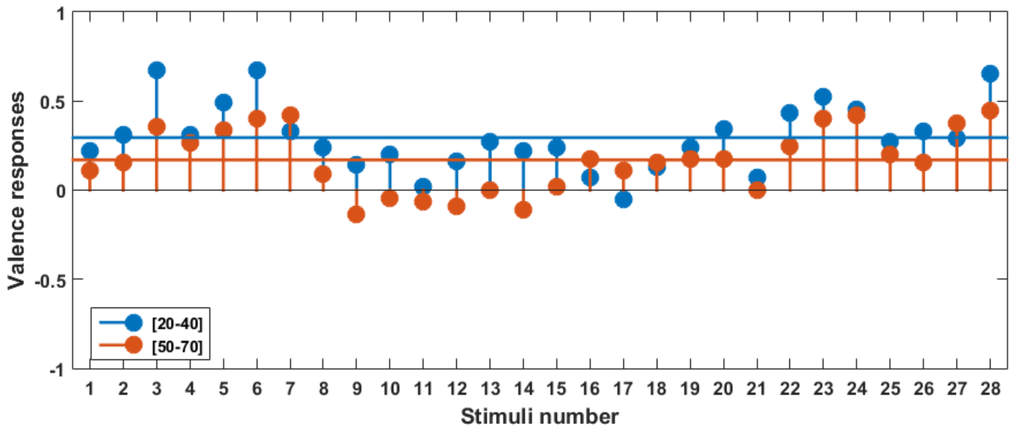


Figure 28: Mean normalised pleasantness response (-1 unpleasant to 1 pleasant) to the tactile stimuli across participants in the age ranges [20,30] and [60,70], using the 6 youngest and oldest respectively to have equal group sizes. Stimuli order: M1 - M7, S1 - S8, T1 - T7, C1 - C7.

From the mean values across stimuli in this graph it can be seen that the participants in the older age bracket appeared to find the stimuli less pleasant. To assess if this difference was statistically significant a pairwise T-test was conducted on the data. The results are shown in Table 13 where this difference is verified as significant for all stimuli. Interestingly, the T-test results for the two age groups across the stimulus types (Music, Tactile or Combination) show that responses by participants in the two age groups were statistically similar for the Music only (M) stimuli. This indicates that their age did not affect musical tastes, but did affect how pleasant they found the tactile sensations; specifically that older participants found the tactile stimuli less pleasant than younger participants. This may be due to a change in skin sensitivity with age.

	T-test result at 5% significance level, across stimuli:			
Null hypothesis H_0	Music only (M1 -M7)	Tactile only (S1-S8,T1-T6)	Combination (C1-C7)	All stimuli
Age group 1 = Age group 2	Accept H_0	**Reject** H_0	**Reject** H_0	**Reject** H_0

Table 13: Results of a paired t-test for Valence responses of participants from two age groups to various sets of stimuli. Age group 1: 6 participants in age bracket [20,30] years. Age group 2: 6 participants in age bracket [60,70] years. All rejected H_0 results found Age group 1 < Age group 2.

Another relation that was investigated was the difference in Valence responses between the Tactile mappings (T1-T6) specifically based on the music samples and the generated Tactile stimuli (S1-S8). It was expected that the simple tactile sensation combinations (S1-S8) would be qualitatively different to mapping from music into the haptic domain (T1-T6) and so the Valence responses would also be different. However, conducting a T-test on this data found that there was statistically no difference between the two groups. Further investigation would be necessary to assess the reasons for the similarity in elicited responses.

As well as the Valence responses, 12 of the participants recorded three adjectives from the list in Table 10. While it transpired that the pleasantness responses alone gave some interesting results, the addition of this data gave a broader understanding of whether the Tactile mappings were effective at eliciting the same affective response as the respective Music stimuli. The data was in the form of 3 words per stimulus so before analysis could be done they were converted into numerical values according to which group, 1 to 8, of the adjective circle they were attributed to. Once this was done, the mean and standard deviation were calculated for every stimulus response and every participant. Since the adjective groupings are arranged in a circle, the circular mean and standard deviation were used by treating values as angles between 0 and 2π. This ensured that groups 1 and 8 were considered to be close together rather than the furthest apart. The mean values were then converted back and rounded to be integer values.

To visualise and compare the adjective responses for the Music only (M) stimuli and the Tactile mappings (T), radial plots containing the spread of responses of all 12 participants in the adjective circle space are shown in Figure 29. Histograms of pleasantness rankings are shown underneath for comparison and the radial plots are rotated to match with the negative adjective groups on the left side and positive adjective groups on the right. The radial plots indicate that the adjectives chosen for the Music and respective Tactile stimuli were generally in the same direction of the space, particularly for plot A (M7) and plot C (M3). However, the Tactile stimulus T7 in plot A was the randomly generated pattern of sensations, so the fact that responses matched for this and the song sample M7 does not verify that the mappings were successful.

While the adjective results for some indicated a slight change in the radial direction within the Hevner space between responses to a Music sample and its Tactile mapping as seen in panels C and D in Figure 29. Both the Valence responses and the mean adjective responses fell mostly in the positive space and it is challenging to draw out any firm conclusions from this. An effort to induce negative Valence responses to Music samples and Tactile sensations would need to be made to assess whether or not the correlations between them are due to chance or not.

To assess the similarity between responses to Music only (M), Tactile only (T) and Combination (C) stimuli the responses per type of stimuli, the adjective responses were treated as sets and the Jaccard set similarity coefficient calculated as shown in Table 14. The Jaccard index is a value in the interval [0,1] for two sets A and B where 1 means that A=B and 0 means that all elements of A are different to B. As can be seen in the table, the mean Jaccard index value was highest at 0.48 for Music and Combination stimuli meaning that responses to these were most similar. This concurs with the pleasantness data in Figure 26 and Table 11. However, all three of the mean Jaccard index values for stimuli types are similar to the value 0.39 of comparing two random sets of the same size and range. This suggests that these index values are not high enough to indicate a significant similarity between any of the responses since they do little better than comparison of random sets.

	Music sample number							
Stimuli types for comparison	1	2	3	4	5	6	7	Mean across stimuli
M vs T	0.26	0.60	0.50	0.26	0.60	0.20	0.60	0.43
M vs C	0.60	0.26	0.50	0.41	0.60	0.50	0.50	0.48
T vs C	0.33	0.26	0.41	0.26	0.50	0.20	0.50	0.35
Random vs Random	0.14	0.33	0.60	0.50	0.41	0.41	0.33	0.39

Table 14: Jaccard indexes of similarity across 12 participants for music samples 1 to 7, calculating the similarity between adjective responses to Music only (M), responses to Tactile only (T), and responses to Combined music with tactile (C) for each song. The results of 7 repetitions calculating a Jaccard index of two random sets (Random) - containing 12 integer elements in the interval [1,8] to match the sets of stimuli - are included for comparison.

To get a better understanding of the spread of adjective responses, the percentage split between responses to individual stimuli was investigated. Results for the percentage of the 3 word responses to stimuli that fall into the cases: all in the same adjective group, 2 of 3 in the same group, or none in the same group are shown in Table 15. The results show that while less than 10% of responses had consistent groupings for all three adjectives, over 50% of results had 2 or more of the 3 responses in equal groups. If neighbouring groups are considered consistent as well then 93.5% of responses were consistent which is a positive result indicating that participants were consistent in their responses. There is little difference in the percentage splits between Music stimuli, the two types of Tactile stimuli and Combination stimuli except a slightly higher consistency in the responses Tactile stimuli. For a random set of numbers the same size and range as the data set, the percentage of adjectives that fell into neighbouring or the same groups was $\tilde{8}0\%$, so the participants were

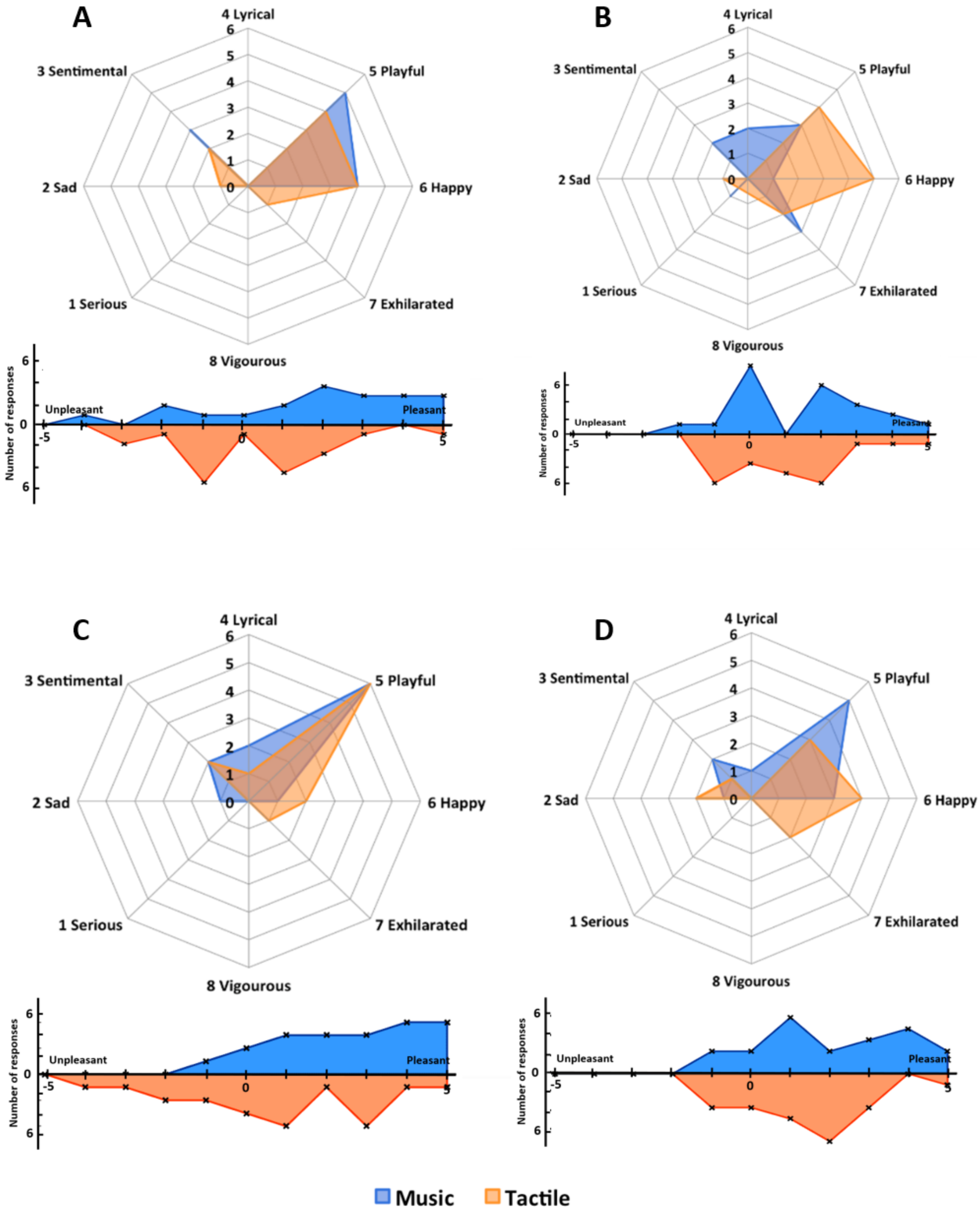


Figure 29: Spread of results across all participants comparing four stimuli presented separately as music and as tactile sensations. Radial plots representing the adjective circle contain the spread of adjective responses across 12 participants (see Table 15). Linear plots contain histograms of the pleasantness rankings of all 20 participants for the music and tactile presentations of each stimulus. The stimuli song samples are A: 'Sweet Sixteen' instrumental (M7, T7). B: 'Soul Bossa Nova' introduction (M4, T4). C: 'Ashes to Ashes' instrumental (M3, T3). D: 'Jaws' theme tune (M5, T5).

more consistent than picking random adjective despite the randomised order of the list they were presented with.

	Percentage (%) of all participant responses for selected stimuli:					
Number of adjectives from the same group	All stimuli	Music only (M1-M7)	Tactile only (S1-S7)	Tactile only (T1- T7)	Combination (C1-C7)	Mean across 30 random sets
All 3	9.23	1.79	2.68	2.68	2.08	0.89
2 of 3	54.5	13.99	13.69	13.09	13.69	33.33
0 of 3 but neighbouring groups	29.76	6.55	7.74	8.63	6.85	45.54
0 of 3	6.55	2.78	0.89	0.60	2.38	20.24

Table 15: Percentage of occasions per participant for which their three adjective responses were either; all in the same group, two in the same group, all in different but neighbouring groups, or all in different groups.

6.6 Comments and limitations

It was common feedback from participants that the adjectives provided - taken from the Hevner adjective circle of emotions evoked by music - were not easily applicable to the tactile sensations. This could suggest that a new list of adjectives needs to be created for tactile sensations because we perceive them differently. Additional words supplied by participants included ‘insistent’, ‘rhythmic’, ‘interesting’ and ‘active’ relating to motion and physical presence. On the other hand it could be that the tactile sensations used were too basic - when mapped from the music samples the complexity was vastly reduced - and actually the same would be commented for playing very simple musical excerpts such as repeatedly playing a single chord or scale. Another possibility is that the medium of tactile sensations such as those used in this project were new to the participants meaning that they had no previous experience of it as a medium through which to communicate emotion and therefore trying to do so was a challenge. Since music is a well-established part of our culture and readily associated with expression of emotion, using the adjectives to describe music was more accessible. This question would be a whole new subject area to explore.

While there was variation between participants in their enjoyment of the sensations created, certain points were repeatedly mentioned. One of the most highly commented was that the ’Jaws’ theme-tune was enhanced by the tactile sensations which added intensity and tension to the music. This gives rise to the possibility of using tactile sensations to enhance cinematic experiences particularly in genres such as thriller, horror and action movies. A number of participants also actively commented that they recognised a few of the Music samples from the Tactile sensations alone. This is a very positive result suggesting clear potential for the use of a haptic interface as a substitute for acoustic music.

An alternative application could be in the gaming industry to create urgency and dynamic sensations beyond the vibration of a handset, giving the user greater immersion in the game. While some participants did not find all of the sensations pleasant they appreciated that they could be used for such applications effectively. The participants that enjoyed the sensations, particularly when combined with music, indicated that a more sophisticated device using the same principles could be really effective to enhance or add interest to music. While individuals might not want such an intense engagement with music in a casual setting, this could have a great effect as an additional element in musical performances or art installations.

7 CONCLUSION

This project has extended the limited research in the field of emotional responses evoked by tactile stimuli and the link between this and music. The principal motivation was to assess the feasibility of using tactile sensations as a substitution for sound to aid deaf users in experiencing music and the experimentation undertaken in this project has made a first step in this direction.

A formal experiment was designed and carried out that investigated the affective responses of 20 participants to 108 parameterised tactile stimuli using a tactor that administered sensations locally to their fingertip. Participants ranked their responses in the circumplex space of Arousal vs Valence. While there was high variation between participants, the set of all results covered the circumplex space indicating that local tactile stimulation is capable of eliciting a range of emotional responses. A gradient of -3.2 was calculated for the first principal component vector of the mean responses across participants suggesting a general negative trend between Arousal and Valence.

Analysis of the results found that frequency of vibration had a strong positive correlation with Arousal responses whereas signal amplitude did not significantly correlate with Arousal. Valence responses were found to correlate strongly with frequency for certain individuals but of the twenty participants, five were positive and ten were negative suggesting that the features of sensations that participants found pleasant were very subjective. Elicited responses also related to the waveform shape of tactile stimuli presented. Square waves elicited greater Arousal responses than sine waves, and α values for envelope waves appeared to negatively correlate with Arousal. This could have been due to the positive correlation between Arousal and the energy in the stimuli signals. To assess how consistent participant responses were, one stimulus was presented six times and the responses for each presentation were compared. It was found that while the responses of all participants were spread across all four quadrants of the circumplex space, only 15.5% of the space needed to be covered to be 95% confident in an individual's response. This indicated that participants were not choosing at random and that their responses were reliable.

The results of this experiment informed the design of a prototype haptic interface that was constructed using a combination of eight vibration motors strapped to the forearm and a squeezing module worn on the upper arm. Audio-tactile mappings were generated by extracting and translating information from the midi files of six music samples onto the tactile space defined by the prototype's interface. A second experiment was conducted to compare the emotional responses elicited by the mappings with the responses to the respective music samples. Participants were also presented with the combination of music with these tactile mappings as well as a set of tactile compositions generated for the device with no musical influence. The stimuli were presented to twenty participants who were asked to rate their Valence response to the sensations and music samples. After eight participants had taken part a modification was made and thereafter participants were also asked to choose three adjectives from a randomised list of 48 taken from Hevner's adjective circle. This modification was made with an aim to improve our understanding of the affective responses elicited by the stimuli.

Results of this second experiment showed that the mean Valence response across all participants were statistically similar for the Music only stimuli and Combination stimuli, whereas Tactile only stimuli were considered statistically less pleasant than the other types of stimuli using a T-test with a 5% significance level. This suggested that the tactile mappings generally did not elicit the same responses as the music, although when combined with music they had no effect. However, inspecting responses to the individual stimuli indicated that for 4 of the 6 tactile mappings the Valence responses of participants were statistically similar to the responses to the respective Music samples. Given that the prototype and mappings were novel creations with multiple limitations, this was a positive result indicating the potential of a tactile interface to be a successful sensory substitute for acoustic music.

Some other interesting effects were noted in the Valence responses.There was no statistical difference found between the responses to tactile stimuli generated from scratch and those mapped from music samples. In addition to this, the responses of participants in the age bracket [20,30] were compared with those in the age bracket [60,70]. It was found that the age had no effect on their responses to Music only stimuli, but all stimuli with a Tactile element were considered less pleasant by the older group of participants. This could be due to a change in skin sensitivity with age and indicates that the age of the target audience needs to be taken into consideration when designing a haptic interface of this kind.

The adjective responses were categorised by the 8 groupings in the adjective circle. Responses were found to correlate between Music stimuli and their respective Tactile mappings. However, the same was also found for a Music sample that was compared to an unrelated, randomly generated pattern of tactile sensations. This could be by chance or indicate that the other correlations were not due to the tactile mappings being effective at eliciting the same emotions as the music samples. A number of participants commented that they recognised some of the music samples from the tactile mappings alone indicating that there is potential for a haptic interface to replicate music for those with hearing impairments. In addition to this some participants commented that a more sophisticated device could also be of use to people with good hearing as an engaging element to enhance their experience of a musical performance or art installation.

7.1 Future work

Two limitations of this project were the unavailability of participants with hearing impairments and the limitations of the prototype used for experiment 2 making it a challenge to create particularly refined or complex sensations. Further experimentation would look to create a more sophisticated prototype with similar features but greater capability for creating subtle and varied sensations. A preliminary experiment could be undertaken similar to experiment 1 of this project to build up a library of sensations specific to the new prototype.

The aim would be to test this refined prototype on both participants who are able to hear and those with hearing impairments. Mappings from music samples that had been evaluated based on genre, aesthetic features, the composer's intended message and general engendered emotional responses would be used to find what emotional responses are recorded when played to hearing people. A record would be kept of the participants' musical capabilities and preferences. Their emotional responses and this detailed set of baseline information would inspire mappings between the music and tactile sensations for the prototype. The set of music samples would be chosen to elicit a greater range of affective responses.

Tactile mappings would be generated by two methods for comparison. Firstly mapping the emotion conveyed using the library of sensations and secondly simulating the rhythms and melody. Including syncronised rhythms is important if the device was used in a setting whereby a deaf user wanted to keep in time with the beat such as in a dance or watching a live music performance, so this may be included in both.

These tactile mappings of the music would then be played to participants with hearing impairments. Their responses would be recorded and compared to see if the emotion and atmosphere of each piece was conveyed accurately in relation to the previous responses of hearing people to the music. Additionally it would be interesting to see the effect of experiencing tactile sensations in a social setting such as listening to music with friends or watching a performance, to see if they reported a greater enjoyment and understanding of the music and sounds by having the tactile sensations.

This further experimentation would really assess the feasibility of using a tactile interface to aid people with hearing disabilities. It would be interesting to see what responses arise to the technology. If the concept was successful then a portable and stylish version of this device could be very beneficial, improving accessibility to various areas of performance art and social situations for those with hearing impairments. It could particularly enrich the lives of those looking to go into the arts vocationally or professionally that may have been deterred due to their hearing.

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